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Journal of Sedimentary Petrology

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 9, NO. 3, PP. 95–104, FIGS. 1–4, TABLES 1–3, DECEMBER, 1939

BEACH SANDS FROM BUNBURY, WESTERN AUSTRALIA

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University of Western Australia

ABSTRACT

The textural and mineralogical features of 15 samples of beach sand from Bunbury, Western Australia are described. The different textures are due to sorting by wave activity which differs on the various beaches. An outline of the geology and physiography of this part of Western Australia is given, and the probable sources of the heavy minerals in the sands suggested.

INTRODUCTION

This examination of the mechanical and mineralogical composition of beach sands was undertaken because it was felt that something could be added to our knowledge of sandy sediments by studying the sands that are accumulating at the present time on seashores. Beach sands, although they do not form any great part of geological formations, may vary considerably within any small area. A record of such textural variation may throw light on similar variations encountered in sediments.

The amount of heavy residue varies in sands and sandstones which are considered to be derived from similar source rocks. The mineral variation in these sands, examined in the light of the conditions under which they are accumulating, shows that the local environment is of great importance, since differences in wave action produce marked variation in mineral contents.

Bunbury, the principal seaport of the southwest of Western Australia, is situated on Koombana Bay, a small inlet off Geographe Bay about 90 miles due south of Perth, the capital (see inset, figure 1). The harbor is, unfortunately, rather shallow, and constant dredging is necessary.

Fifteen samples of sand were collected from the beaches around Bunbury at the positions shown in figure 1. The local conditions vary slightly for each sample. Taking those from the ocean beach first, the most southern, no. 5 and no. 6 are from a moderately wide beach with a fringing platform of sandy limestone. Numbers 7a and 7b, a little farther north, are from a beach between two small headlands of sandy limestone but the water near the beach is moderately deep. Number 14 is from the main wide beach, about half a mile long, which lies between platforms of tholeiite (at the north) and sandy limestone (at the south). The water is deep and the sand is coarse and yellow with abundant shell fragments. Numbers 8 and 11 occur under similar conditions. Numbers 9, 10, 12, and 13 are from within Koombana Bay where there are no rocks except those brought to build the breakwater. These sands are soft, pale yellow, and contain abundant foraminifera. Numbers 4, 3, 2, 1, and 15 are from the southeastern beach of Koombana Bay and are fine white sands with few shell fragments. Each sample was collected just above the waterline, at the landward edge of Johnson's foreshore zone (4, 161).

Before discussing the details of these sands, it is necessary to give a brief outline of the geology and physiography of the surroundings of Bunbury.

GEOLOGICAL AND PHYSIOGRAPHIC SETTING

Geology:—There has been no detailed geological survey of Bunbury since that made by Gibb Maitland in 1897 (7). The information used in compiling figure 1

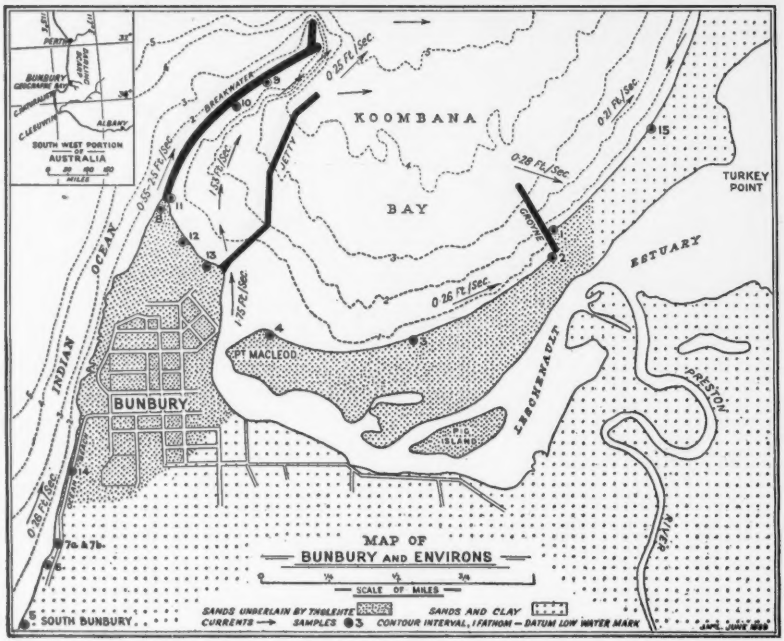

FIG. 1.—Map of Bunbury showing the geology, depth of harbor, direction and strength of currents, positions of sands collected. (Tholeiite extending beneath the harbor has been omitted for clearness.)

Compiled from Public Works Dept. W. Australia plan No. 21923 and Admiralty Chart No. 1034. Geology from bore records.

was obtained from the Public Works department, Western Australia, through the courtesy of Mr. J. Stevenson Young, who made many unpublished plans and bore records available. The soundings were obtained from Admiralty charts.

The principal geological formations are sands and clays, and a flow of tholeiite (3) exposed on the ocean front between the breakwater and the ocean beach, but elsewhere covered by sand dunes. The flow has been encountered by borings at depths between 20 and 35 feet below low water mark in the harbor. The tholeiite is considered to be Tertiary, whereas the sands and clays are Recent, but some, encountered in various bores, may be much older.

A coastal plain extends between the ocean and the Darling Scarp which is the western edge of the great Western Australian plateau (5, 83–85). The coastal plain is composed of the above mentioned sands and clays, with scattered remnants of the tholeiite flow.

Pre-Cambrian gneisses, granites, and greenstones occur on the plateau and Darling Scarp and also in the Naturaliste-Leeuwin area in the southwest. Flanking the western side of the Scarp about 15 miles southeast of Bunbury, and running south, there is a series of sandstones which are correlated with the Permian sediments of a coal basin to the east.

Physiography:—At Bunbury the coast-

line is broken by the outcrop of tholeiite, and by fringing platforms of sandy limestone. Elsewhere it is smooth and consists of sandy beaches backed by dunes of considerable height for this part of the coast is exposed to the full force of westerly winds.

At Cape Naturaliste, the coast is steep and rocky with deep water up to the cliffs. Rivers immediately north of the Cape are almost stagnant and only reach the sea by artificial channels. They differ from those near Bunbury which have been rejuvenated at least twice in fairly recent times. The coastline between the Cape and Bunbury is smooth with narrow sandy beaches and low sand dunes.

The tholeiite flow at Bunbury formed a reef against which the materials brought down by the Preston and Collie Rivers was deposited. (The Collie River is about three miles north of the Preston at its mouth, and therefore not shown on figure 1.) These rivers now discharge into the Leschenault Estuary, a wide shallow sheet of water which is gradually becoming dry land at its northern end. Separating the Estuary from Koombana Bay is a narrow belt of sand dunes, standing in part on the eastern continuation of the tholeiite flow.

Admiralty charts show that the continental shelf slopes very gently, and not until the Naturaliste Reefs have been passed at about 35 miles west of Bunbury is a depth of 30 fathoms reached. West of the Reefs the slope is rapid and within a few miles 100 fathoms is reached. Soundings in Geographe Bay show that the floor is covered with fine sand, and occasional accumulations of gravel and shells, but no mud. In winter when the Preston and Collie Rivers flood, a great deal of muddy material can be seen entering the sea, but this is mostly removed, as the soundings show, to some distance out to sea.

This part of Western Australia has a winter rainfall of about 36 inches. The prevalent winds during winter are from the northwest, west, and southwest, and often reach gale force. In summer land and sea breezes are of almost daily occurrence, but there are also strong easterly winds. All these winds influence the waves on the beaches and cause currents which are longshore drifts. The main current up the Western Australia coast is from the south.

In order to protect the harbor from the westerly and northwesterly gales in winter, a breakwater was built in about the year 1900, and later extended. This breakwater was built on a reef through which there was a natural discharge channel for the water from the Leschenault Estuary. Sand accumulated quickly in Koombana Bay as can be gathered from a report by F. J. Ramsbotham (10), "From a survey . . . it was ascertained that the beach between jetty and breakwater had advanced at the level of low water 200 feet since 1903, or 20 feet per year." No figures are available for the next 25 years, but the accumulation, though continuing, does not appear to be so great, possibly because of dredging.

Pt. MacLeod is another part of Koombana Bay where sand accumulates, and a spit is forming. A comparison of old and new charts shows that in places near Pt. MacLeod the one fathom line has moved towards the center of the Bay 200 yards since 1885. It is on record that over 4,300 cubic yards of sand accumulated on the shore in this vicinity after a particularly severe gale. A groyne has lately been built to prevent sand from drifting down the eastern side of the Bay to the center. The groyne was finished about three years ago and has been responsible for the accumulation of 7,000 cubic yards of sand annually. The increased size of the beach due to this accumulation is shown in figure 1, while the shallowness of the Bay can be seen from the fathom contour lines. The new land at Pt. MacLeod is already considerable for a line of low cliffs marks the inner edge of a former beach, several hundred yards south of the present beach.

MECHANICAL COMPOSITION OF THE SANDS

The sands were dried and sieved through a set of Tyler sieves giving the Wentworth grades.

Table 1. *Mechanical analyses of the sands*

Percentage retained on: Screen openings (mm.):	9 1.98	16 0.99	32 0.49	60 0.24	115 0.12	250 0.06
	%	%	%	%	%	%
Sample no. 1	0.06	—	0.25	77.3	18.5	3.9
Sample no. 2	—	0.03	5.08	61.34	30.1	3.47
Sample no. 3	—	—	3.92	82.86	11.4	1.78
Sample no. 4	—	—	0.72	65.9	32.3	1.05
Sample no. 5	—	0.02	7.86	47.93	42.1	2.09
Sample no. 6	0.16	1.13	6.54	17.6	69.0	5.48
Sample no. 7a	—	0.49	36.1	56.5	6.4	0.44
Sample no. 7b	—	0.54	19.1	32.8	45.1	2.46
Sample no. 8	0.04	0.67	38.6	54.8	5.7	tr.
Sample no. 9	—	0.01	0.63	39.3	54.8	5.23
Sample no. 10	—	—	0.04	41.8	55.1	3.03
Sample no. 11	0.07	0.47	58.1	37.7	3.3	0.33
Sample no. 12	0.03	0.18	4.6	84.7	9.9	0.56
Sample no. 13	—	—	0.9	55.9	40.8	2.3
Sample no. 14	0.43	1.57	43.0	42.8	11.2	0.97
Sample no. 15	—	—	2.4	76.8	16.8	3.87

Direct cumulative plots were made from these figures, and the Equivalent Grades and Grading Factors calculated by Baker's method (1, 363).

Figures 2 and 3 show the Equivalent Grades and Grading Factor respectively. In these diagrams the samples are arranged in sequence from the most southerly part of the ocean beach to the most easterly part of the Bay beach.

from the ocean beaches are much coarser than those from Koombana Bay. Figure 3 shows that all the sands are fairly well-sorted, the most perfectly sorted being from the Bay where the water is quieter and less subject to violent waves.

The figures of table 1 were drawn as curves in figure 4.

From figure 4 it is seen that there are three distinct texture groups of sand:—

1. Rather poorly sorted with the maximum in grade +32 and a secondary maximum in the next finer grade. Numbers 11 and 14 from the ocean beach.

2. Well-sorted sands with the maximum in the +60 grade. Numbers 1, 2, 3, 4, 12, and 15, from Koombana Bay.

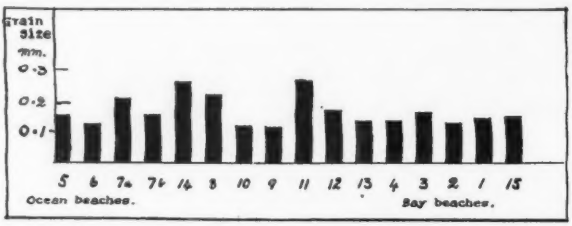

Fig. 2.—Equivalent grades of the sands.

From the variation in Equivalent Grade it is readily seen that the sands

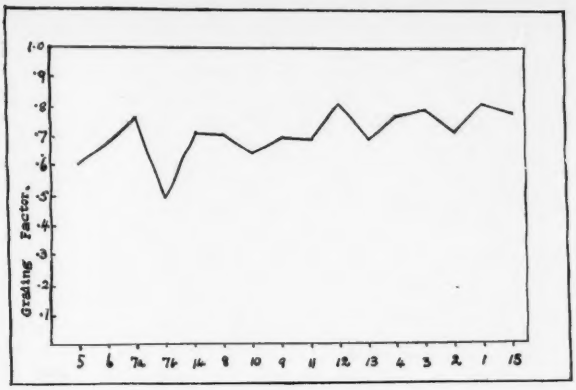

FIG. 3.—Grading factors of the sands.

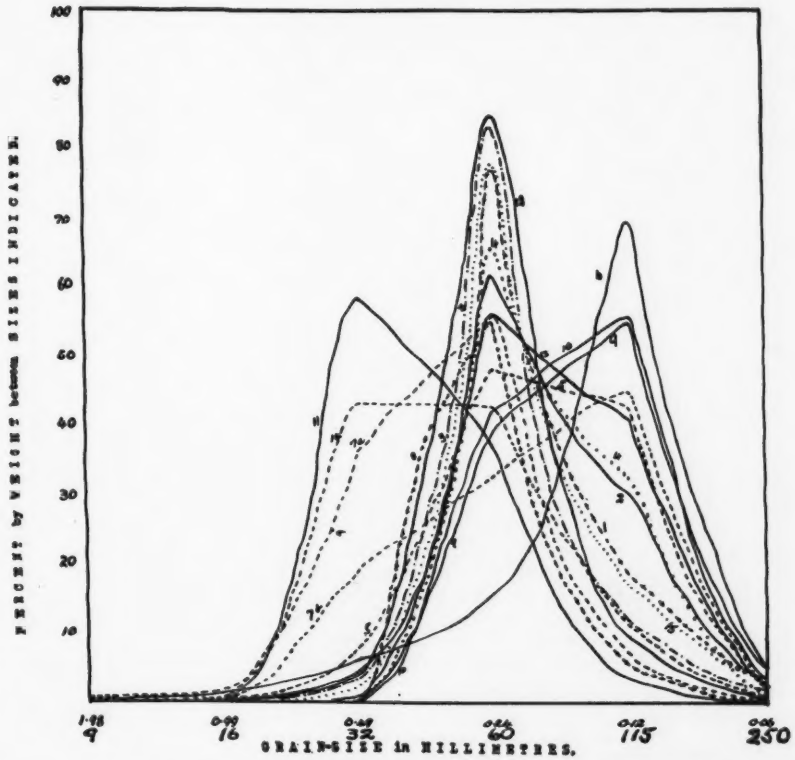

FIG. 4.—Frequency curves of mechanical analyses of Bunbury beach sands. The sieve numbers have been added beneath the grain-sizes.

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3. Fairly well-sorted with the maximum in the +115 grade. Numbers 6, 9, 10, 13. With the exception of no. 6, these are from the beach between the jetty and breakwater.

Numbers 5, 7a, and 7b, 8, do not seem to fit into any of these groups.

The sands from the ocean beach are coarse and possess secondary maxima which indicate that the sorting is not complete. An interesting point is that this beach is never hard and firm, like some of those in the Bay. This softness has been explained by Kindle (6) as being due to the shell fragments which "reduce the effective operation of the binding influence of capillarity and thus prevent the formation of a hard beach." Another factor here is that fairly deep water comes in near the platform of tholeiite at the northern end of the main beach and stronger wave action takes place causing the accumulation of coarse material at the expense of fine which is swept out to sea.

Number 6 is a sand in which some coarse material still remains, but the sand as a whole is fine-grained. Number 5 is a typical sand from the southern portion of the beach.

The sands from Koombana Bay near the groyne show nearly perfect sorting. Numbers 9, 10, and 13 contain a great deal of organic material in the form of minute spicules, foraminifera, and shell fragments. It is difficult to know whether this should be removed before a mechanical analysis is made or not. It was felt that the whole of the material represented the sand, so it was not removed.

Number 7b is an imperfectly sorted sand, and the mixing was obviously done by waves just prior to collection, for swash marks of sand and seaweed still were fresh. It was collected to compare with 7a, the sand from a small bank which had been cut into by the sea. This locality has rather deep water almost to the shore as it is in a little bay between headlands of sandy limestone.

The movement of sand on beaches is due principally to wave activity, but it is beyond the scope of this paper to discuss the many aspects of wave action on sands. Sorting by waves and currents has been summarized elsewhere (9, 87).

Within Koombana Bay the waves strike the eastern shore obliquely and a longshore drift is set up. The waves gradually work along the beach with a creeping action which is excellent for lifting out the finer grains and moving them slightly towards the south all the time. On fine days the gently lapping waves can be seen doing this work, and ripples parallel to the shore are also formed. That this wave sorting is effective is shown by the accumulation on the east side of the groyne as mentioned before. Heavy minerals are concentrated on the beach east of the groyne, and when this beach is cut into banks by waves, the heavy dark-colored minerals are seen in thin bands, similar to those described by Thompson (13, 726, and pl. 1). The sand dunes behind the beach also contain a large quantity of heavy minerals.

Most of the currents shown in figure 1 would not alone be effective in moving sand, as it has been found (12) that a current of 0.5 feet per second is required to move sand grains 0.01 inch in diameter, or about equal to those just retained on a no. 60 Tyler screen. The current flowing from the mouth of the Estuary is sufficiently strong to move sand and is responsible, with the co-operation of wave activity, for the sand accumulating within the breakwater. Even before this breakwater was built sand tended to accumulate on a tholeiite reef, but the breakwater is a much more effective barrier. Sand has also been forced around the end of the breakwater by waves and winds from the west and southwest, but this has been partially stopped by building a northwest extension. Sand and seaweed have been carried right up on to this end of the breakwater, 20 to 30 feet above the sea.

The tides in Koombana Bay have very little influence on sand movement. There is only one tide every day, and that only of a foot or two.

From observations at the Ocean Beach it was found that under strong westerly winds the beach is cut back almost to the roadway (in summer the beach is 200 to 300 yards wide) and well-rounded tholeiite boulders are exposed in places. The sand is carried out from one end of the beach, and, when the wind conditions are favorable, returned to the other. Any fine sand is moved away, and the sand appears to be a coarse residue in the process of being ground finer. Occasionally in summer fine sand is found in the sea within 100 yards of the beach, but it is never on the beach. The currents along this part of the coast are from the south, but are of low velocity. Nevertheless when waves have moved out the finer grains in suspension these will tend, because of the current, to be moved slightly northwards, hence there is a potential sorting of the finer sand towards the breakwater. Another factor assists the production of coarse sand on this beach, the depth of water here is greater than it is in Koombana Bay, and the beach faces the open ocean so that waves are bigger and stronger. Cornish (2) states as a general law for the movement of material on beaches that "the grain (size) of the beach is coarser where the beach is exposed to the heaviest breakers," and this is found to be true of the sands examined.

MINERALOGY AND ORIGIN OF THE SANDS

An inspection of the mechanical analyses shows that for most of the sands the +60 grade is the most prevalent, although the +32 is the most prevalent in the two coarsest sands. Accordingly grades +115 and +250 were separated in bromoform to obtain the heavy minerals (+ here means retained on; +250 indicates that the sample has passed the 115 mesh sieve and is retained on the 250).

TABLE 2. *Beach sands, Bunbury. Heavy minerals in the +115 grade.*

Max. in grade	+115															+60
	+60	+60	+60	+60	+60	+115	+60	+115	+60	+115	+60	+32	+60	+60	+32	+60
Index Fig.*	25.5	.35	6.3	.65	.25	.10	3.2	.45	.35	.15	.40	.61	.20	.10	1.43	33.2
Sample no.	1	2	3	4	5	6	7a	7b	8	9	10	11	12	13	14	15
Minerals																
Magnetite	A		a													A
Ilmenite	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Calcite		a		+	+	+	+	+	+	a	a	+	a	a	+	
Amphibole	+	a	a	a	a	a	+	a	+	+	a	+	+	+	+	+
Tourmaline	+	+	+	+	+		+	+			+	+		+	+	+
Leucoxene	+	+	+	+	+	+	+	+	+	+	+	+	+		+	+
Garnet	a	+	+	+	+	+	a	+	+	+	+	+	+	+	+	+
Epidote	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Kyanite	+		+		+	+	+	+	+						+	+
Zircon	+					+	+	+	+						+	
Rutile	+					+			+						+	+
Monazite						+									+	
Zoisite								+								
Staurolite	+							+			+					+
Corundum									+			+				
Sphene																

A = very abundant; a = abundant; + = present but not in large amounts.
* Index figure is the per cent by weight of heavy minerals in the sample.

The concentration of heavy minerals by natural panning similar to that of a beach placer deposit is very high in numbers 1, 3, and 15. After the magnetite was removed with a small electromagnet the remaining dark-colored grains, presumably ilmenite, were removed by fusing part of the heavy residue with $KHSO_4$ in a small crucible. The light colored infusible grains were recovered by taking the fused mass into solution with *warm* water. The use of this salt

TABLE 3. *Beach sands, Bunbury. Heavy minerals in the +250 grade.*

Index Fig.*	100	4.9	80	6.6	12.5	2.4	11.4	11.4	.95	3.9	3.0	1.7	.42	31.9	100
Sample No.	1	2	3	4	5	6	7a	7b	9	10	11	12	13	14	15
Minerals															
Magnetite	A		A											A	a
Ilmenite	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Calcite		+	+	+	+	+	+	+	+	+	+	+			
Amphibole	+	a	+	a	+	a	+	+	a	a	a	+	a	+	+
Tourmaline		+		+	+	+		+	+	+	+	+	+	+	
Leucoxene	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
Garnet	+	a	+	a	+	+	+	a	+	+	+	+	+	+	
Epidote	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
Kyanite		+		+	+	+		+	+			+	+	+	
Zircon	+	+	a	+	+	+	+	+	+	+	+	+	+	a	a
Rutile	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Monazite	+		+											+	+
Zoisite					+	+	+				+	+	+		
Staurolite		+		+	+	+			+		+		+		
Sillimanite		+	+					+	+			+			
Sphene			+	+	+	+			+	+	+	+	+		+
Apatite					+	+			+	+	+	+	+	+	
Pyroxene		+	+	+	+	+	+	+	+	+	+	+	+		
Spinel															+
?Topaz			+												

A = very abundant; a = abundant; + = present but not in large amounts.
* Index Figure is the per cent by weight of heavy minerals in the sample.

was first advocated by Mackie (8). The remaining grains were thus concentrated and appeared to better advantage.

It is noticeable that with the increase of the index figure in the finest sand *examined (table 3), there is also an in*crease in the number of minerals. No percentage figures for individual minerals were obtained, and the relative abundances given are estimates.

There are a number of possible sources for these heavy residues:—

1. The Recent to Sub-Recent sands, clays, and limestone of the coastal plain.

2. The tholeiite flow underlying the town of Bunbury and outcropping on the beach.

3. Permian sandstones.

4. Pre-Cambrian complex of the Darling Scarp and plateau.

5. Pre-Cambrian rocks brought from the Scarp to build the breakwater.

6. Pre-Cambrian gneisses of the Naturaliste area.

1. Little is known of the Tertiary to Recent geological formations in this part of Western Australia, but it appears that the sands and clays have been derived from the weathering and transportation of Pre-Cambrian material, for the Darling Scarp is in a complex of gneisses and granites. The Collie and Preston rivers must have been responsible for much of the material of the plain. From the worn appearance of zircon, kyanite, tourmaline, and monazite it is probable that they have passed through several cycles of sedimentation.

2. Magnetite, ilmenite, and pyroxene occur in fresh angular grains. The tholeiite has doubtless provided pyroxene, and probably much magnetite and ilmenite; but it is difficult to be certain that magnetite and ilmenite do come only from the tholeiite, as they are, especially ilmenite, common to a great many beach sands where no basic source rock is present. When tholeiite weathers to soil the pyroxene is quickly changed to a clay mineral, whereas under marine disintegration some of the pyroxene remains. Pyroxene is a fairly persistent, though not a prominent, constituent of the heavy residues.

3. Permian sandstones are cut through by the Preston River when it leaves the Scarp and flows out on the coastal plain. The redistributed sand from these sandstones may have given rise to some of the unconsolidated sands of the plain. The sandstones contain abundant zircon in worn grains, tourmaline, worn kyanite

and rutile. All these are similar in appearance to the same minerals in the beach sands.

4. As the rivers have short courses from the Scarp to the sea it is probable that some fresh material has been brought down. Amphibole is almost certainly from this source, and it is possible that epidote and zoisite may have come in as well. The former is a stable mineral which can survive long transport so that it may also be present in the sands of the plain. Zoisite is regarded as less stable than epidote, and it is not recorded from sediments and sands nearly as often as epidote. It is a mineral characteristic of metamorphic rocks, and its source is likely to be in the Pre-Cambrians of the drainage area.

5. The influence of the breakwater rocks, fresh gneisses, granites, and greenstones brought from the Darling Scarp, is not easily determined, though presumably some weathering and disintegration must have taken place during the last 35 years or so. These rocks are potential sources of hornblende (the actinolitc variety common to epidiorites), zoisite, epidote, apatite, and zircon. No attempt was made to distinguish between the different types of zircon found in the sands; most of the grains were of the rounded prismatic type, but a number of fresh unworn grains were also seen.

6. Garnet is a mineral which is present in practically all the sands. It occurs in fresh angular fragments and occasional small dodecahedra. So far as is known to the writer no garnetiferous rocks are in the breakwater, so that the source of this mineral must be sought elsewhere. It may have come in with the sands and clays of the coastal plain, but its angularity suggests a source nearer at hand; or, a source which has been tapped later in the history of the sands. The nearest known garnetiferous rocks occur in the valley of the Preston River, some 35 to 40 miles southeast of Bunbury, and the grains may have come in with others carried down by the river. Another possible source for garnet is the gneiss which outcrops on the coast near Cape Naturaliste. In a direct line the Cape is about 30 miles south-southwest of Bunbury. Ilmenite-garnet sands occur in patches on the beaches near the Cape, and it is possible that garnet and ilmenite from this source have been distributed to all the beach sands.

The light fraction of the sands was examined in three grades, the +60, the +115, and the +250. Quartz is the principal constituent, but feldspar, shell fragments, and Foraminifera are also present. The feldspar includes orthoclase, plagioclase, microcline, and microperthite. The +250 grade contains the greatest amount of feldspar. The plagioclase is probably derived from the tholeiite or from the breakwater rocks. The quartz grains are not rounded, angular to subangular grains being predominant. The grains are rather more rounded in the coarser grades, but the general appearance is that of angularity.

The carbonate content of the sands is as follows:—

Sample No.	% $CaCO_3$*
5	32
10	15
12	54
14	20
15	7

The quantity of calcium carbonate indicates to a certain extent the quantity of organic remains. Number 12 is from a part of Koombana Bay where the conditions are quiet, and therefore suitable for the growth of animals, particularly Foraminifera; whereas number 15 is on a shore which is subject to continual wave action which causes the removal of the lightest material.

CONCLUSIONS

The textural features of these sands reflect the local conditions of wave activity to which they have been subjected. The consideration of such a series of mechanical analyses from a small area may help to elucidate the conditions

* By leaching with NCl.

under which textural variations have been caused in sediments which are now consolidated.

The grade in which the heavy minerals occur is of importance when describing sediments, for if the grade containing the maximum amount of the sediment is examined for heavy minerals it does not give a true idea of the quantity of minerals present. This has already been pointed out by Rubey (11). The variation in heavy mineral content is interesting, for it shows that even in one small area great differences occur. In a consolidated sediment such a variation might be considered to represent different periods of deposition.

This investigation shows, too, that lateral variation, in amount if not in the minerals present, due to local conditions of accumulation or sedimentation will be the usual rather than the unusual occurrence in beach sands, and may also be so in other sediments deposited under more uniform conditions.

ACKNOWLEDGMENTS

I wish to acknowledge my indebtedness to Mr. J. Stevenson Young, chief of the Harbours and Rivers branch of the Public Works department, Western Australia, who willingly made available many unpublished reports and maps of the Bunbury Harbour without which this paper could not have been written.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 9, NO. 3, PP. 105–121, FIGS. 1–4, TABLES 1–10, DECEMBER, 1939

THE SEDIMENTS OF DEVILS LAKE, A EUTROPHIC-OLIGOTROPHIC LAKE OF SOUTHERN WISCONSIN

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ABSTRACT

The sediments covering the bottom of Devils Lake below the depth of about six meters are fine muds. Above six meters they increase in coarseness with decrease in depth to become sands or coarser materials on the shores. The immediate bottom of the lake at short distances from the shores is covered with a black soupy liquid that is termed sludge. This has a maximum thickness estimated as about one meter. The sediments beneath the sludge are black and have an average water content of 82.5 per cent. Silicon dioxide is the chief constituent of the inorganic part of the sediments and ranges in percentage between 50 to more than 60 per cent. There is little or no calcium or magnesium carbonate. The organic content of the sediments is estimated to be between 15 and 20 per cent. Bacteria are not particularly abundant in the muds beneath the sludge, but aerobic and facultative bacteria average over a million per gram of dry sludge.

INTRODUCTION

Devils Lake is situated in Sauk County in the southern ridge of the Baraboo Range, an inlier of folded pre-Cambrian rocks in the midst of undeformed Lower Paleozoic limestones and sandstones. The Baraboo Range is probably better known to most geologists of the upper Mississippi Valley than any other area of that region and it is annually visited by field parties of students from neighboring universities and colleges. The geology is of great interest and many problems are not known to have been solved. The pre-Cambrian rocks are in synclinal position of east-west trend. The east end of the syncline is closed and the axis pitches west. The structure on the west end is not fully understood. The pre-Cambrian strata consist primarily of a great quartzite formation with thickness of 3,500 feet. This, so far as known, rests on various igneous rocks and it is overlain in the deeper parts of the synclinal basin by slate, dolomite, iron ore, and quartzite.

Prior to deposition of the lower Paleozoic strata the quartzite formed a high ridge around a lowland cut on the weaker rocks of the central part of the syncline. This ridge was surrounded by a lowland cut on the rocks beneath the quartzite. Burial of the region beneath the lower Paleozoic strata concealed the pre-Cambrian rocks and surface, but later exhumation has exposed both to some extent. The streams responsible for the uncovering were superposed on the pre-Cambrian and some of these cut gorges through the old quartzite ridge. The precurser of the Wisconsin River cut the gorge in which Devils Lake is now situated.

The Wisconsin ice sheet entered the Devils Lake gorge from both ends and began its final retreat when the two tongues were about a mile apart. A basin then existed between the two tongues and this became filled with melt water, and melt water silts, clays and sands were deposited over the entire bottom of the basin then submerged. Each tongue left a frontal moraine which remained as a dam after retreat of the ice sheet. The lake then also fell to the level of the lowest place over the moraines and thus exposed some of the deposits formed when the lake level was higher. The moraines are composed of a vast variety of materials in the range of dimension from clay-

size particles to large boulders and have a range of lithic composition of sandstone, conglomerate, dolomite, quartzite and a considerable variety of igneous rocks. Exposed basinward from the moraines are outwash and lacustrine sands, silts, and clays which were deposited in the stream known as Messenger Creek. These features are shown in figure 1.

Devils Lake has an area of about 0.6 square miles when full to its ordinary shores. The dry weather of the past 10 years has produced considerable shrinkage. Drainage into the lake is from an

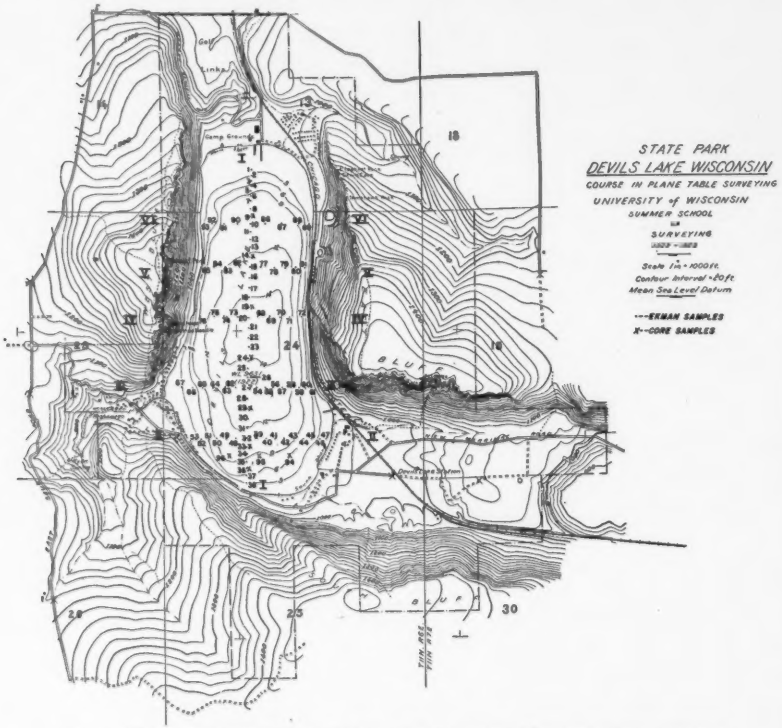

FIG. 1.—Map of Devils Lake and Devils Lake Region. Numbers show positions from which samples were obtained.

lake when its level was higher and some of its shores were ice bound.

The present shores of Devils Lake are composed of lacustrine sands, silts and clays adjacent to the moraines on the north and southeast ends and of quartzite cliffs flanked by quartzite talus elsewhere, except on the southwest where a small delta has been built by a little area of about 5.5 square miles. There are two inlets of which one known as Messenger Creek enters the lake on the southwest margin. The other flows into the lake on the east end of the north side. Both are small, but there is flow rather generally throughout the year except in very dry seasons, when it becomes small or even wanting. Messenger Creek drains

sandstone and quartzite terranes which are composed almost entirely of quartz and hence that is about all that may be acquired and brought to the lake. Similar conditions obtain in the small creek entering the lake on the northeast margin except that it flows through glacial deposits for a short distance before entering the lake and may acquire some sediments from these. Messenger Creek also flows for a short distance over materials which, in part, are of this stream's building and perhaps, in part, were made on the bottom of the lake when it was larger.

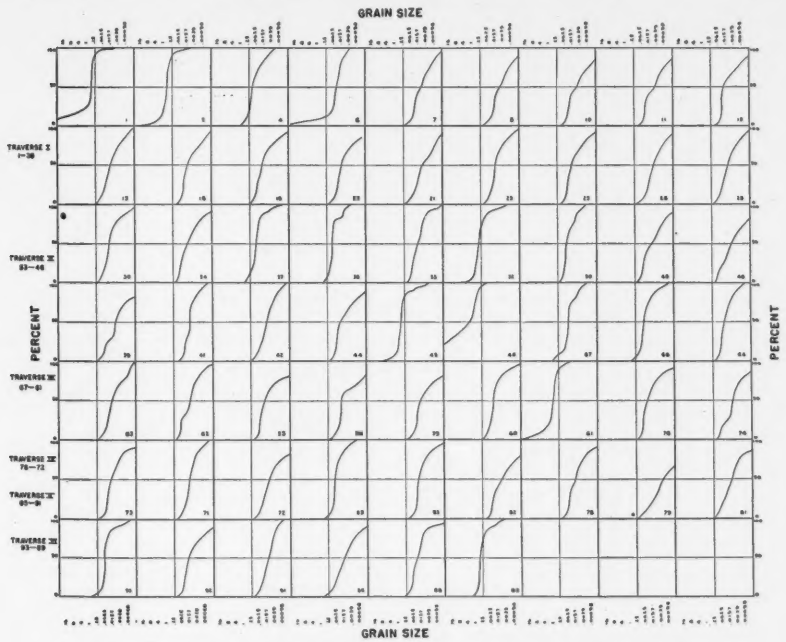

FIG. 2.—Cumulative curves of samples obtained with Ekman dredge. Numbers correspond to those of Fig. 1.

Devils Lake has no outflow other than what may be brought about by seepage through the surrounding materials. There are some springs south of the moraine on the southeast margin of the lake which may obtain water from this source. It is not known that such is the case and it seems somewhat difficult to understand how water could pass through the fine-grained sediments that cover the bottom and the margining silts and clays that form the fine-grained deposits margining the southeast and north shores. It is possible that most of the inflow is lost by evaporation from the lake and margining materials and as the inflow contains little dissolved matter there is no reason to think that there would be a serious increase in salinity.

The maximum depth found for Devils Lake in the sampling done by the writers was 14 meters and if the lake stood at its ordinary shores the maximum depth would be about ½ meter more. The place of greatest depth is about three-seventh

of the distance from the south to the north end. The depth contours in meters are shown in figure 1.

The water in Devils Lake is soft and the substances in solution in parts per million (waters collected on the surface in November, 1908) are as follows (5).

	parts per million
SiO_2	2.2
Fe_2O_3 & Al_2O_3	0.7
Ca	3.2
Mg	1.1
HCO_3	8.4
SO_4	8.1
Cl	8.2
Total	31.9

If the calcium and magnesium are in the form of carbonates, the former is eight parts per million and the latter 3.4 parts per million. Neither of these is a large quantity. Compared to Lake Mendota, a hard water lake, the quantity of calcium is about one-seventh (3.2 to 23.4 average) and magnesium about one-twentieth (1.1 to 22.7 average). The lake waters are on the border line between eutrophic and oligotrophic.

The sediments of Devils Lake were studied because of the great interest the Baraboo region has for geologists, the general interest the lake has for the thousands of visitors who annually come to its shores, because Van Hise and his associates established extremely important geologic principles in the region, because it is a lake surrounded almost exclusively by siliceous terranes, and because of its rather unique geologic history and present environment.

Study of the sediments of Devils Lake was made possible by a grant from the Graduate School of the University of Wisconsin from funds placed at its disposal by the Wisconsin Alumni Research Foundation. This support is gratefully acknowledged. Construction of the samplers was financed by a grant to the senior author from the Bache Fund of the National Academy of Science. The chemical analyses of the sediments were made by W. A. Broughton. The sampling was done by the authors assisted by W. A. Broughton, A. E. Buckhan, and A. S. Kunsman, all graduate students in the University of Wisconsin. The writers are indebted to Miss Janice Stadler of the Department of Bacteriology of the College of Agriculture of the University of Wisconsin for studying the bacteria living in the sediments.

METHODS OF SAMPLING

The sampling was done in the winter of 1937–1938 when the lake had a cover of ice with thickness of more than one-third meter. Samples were taken at distances of 15 to 20 meters apart. Distances were determined by pacing on the ice and the sampling was done through holes. Six traverses across the lake were made, one from north to south and the long diameter of the lake and five from east to west across the lake. Sampling was mainly done on these traverses by means of an Ekman or clam shell sampler, and a total of 96 samples was thus taken. These are indicated on figure 1 by simple numbers. Over the bottom composed of fine sediments 10 core samples were taken with a core sampler devised by the senior author. These are indicated by numbers followed by a cross. The sampler is thought to have penetrated the mud to depths not greater than three meters and the cores obtained did not exceed 1.2 meters. The sampler can not obtain a core of sands.

SOURCES OF THE SEDIMENTS ON THE BOTTOM OF DEVILS LAKE

The two streams entering Devils Lake are not contributing very large quantities of sediments and particularly very little of a clastic character. This probably has been the case since the region was clothed with vegetation. Some sediments enter via the atmosphere and it seems likely that the contributions from this source have increased within recent years. Organisms account for some sediments as the lake supports a considerable diatom population. Macroscopic aquatic plants are probably the largest contributors,

but this statement can not be given finality. The plant matter consists largely of finely divided and fibrous particles. The quartzite cliffs and talus are not thought to have been of much importance as a source for sediments. It is thought that the sources of greatest importance are the shores and shallow bottoms composed of sands, silts and clays originally brought into the region by the ice sheets. These are stirred and the shores attacked when the waves are running and the waters then become turbid and thus have their densities increased. This creates a turbidity gradient inclined toward the bottom of the lake and there is thus movement of the turbid waters to deeper bottoms where the movements are checked, and the silts and clays settle from suspension. Little sand is brought to these bottoms by water currents. Some sand is blown from the shores upon the ice in winter whence it settles to bottoms of every depth when the ice melts.

DISTRIBUTION OF BOTTOM SEDIMENTS

The shallow water sediments adjacent to the shores, to a greater or lesser degree, reflect the characters of the shores. Where the shores are built of melt water and lacustrine deposits of the greater Devils Lake the deposits of the adjacent bottoms are composed of sands. This is the case on the northern and southeastern shores. The sands pass into clays and silts on the east, west and south sides of the lake at a distance of about 45 meters from the shores and at a depth of about 6 meters. On the southeast side the sands pass into the finer sediments at a distance from the shores of about 150 meters and in a depth of water of about 6 meters. On the north end the sands extend outward about 250 meters and to depths of about 6 meters.

OBJECTIVES OF STUDY

The sediments were studied for general composition, stratification, color, physical composition in terms of dimensions, water content, chemical composition, loss on ignition, matter of organic origin, shells and tests of organisms in the sediments, oil content, and bacteria in the fine sediments.

COMPOSITION OF SEDIMENTS

The sands consist mainly of quartz. There is considerable feldspar and biotite, and ferro-magnesian minerals are common. There are also occasional small fragments of various kinds of rocks. These are not common. The sources of the minerals are largely the deposits made by the ice sheets. The silts have composition similar to the sands. The minerals of clay size have evidently a wide range in composition. They contain some finely divided quartz, some clay minerals, and some tests of diatoms and spicules of sponges.

In general the sediments are well to normally sorted as may be seen from the cumulative curves shown on figure 2 and the coefficients of sorting given in tables 1 and 2.

STRATIFICATION IN THE SEDIMENTS

No stratification of any kind has been seen in any of the muds derived from the bottom of Devils Lake. The sands adjacent to the shores exhibit stratification where these sands have been studied. The absence of stratification in the fine sediments is referred to stirring and mixing of each successive deposit of sediments with the sediments previously deposited, the mixing being referred to the activity of bottom organisms. However, no bottom organisms other than small worms have been seen.

COLORS OF THE SEDIMENTS

The sands of the shallow waters adjacent to the shore range in color from white to light yellow. The muds are black when wet and dark gray to grayish-black when dry. The darkness is due to the presence of organic matter and not to ferrous sulphide, and the blackness, to the extent the organic matter is not eliminated by microorganisms, will be retained on lithification.

TABLE 1. *Constants of sizing of the sediments of the present bottom of Devils Lake (sludge in connection with cores omitted)*

M—median; Q_1 and Q_3—first and third quartiles; So—coefficient of sorting; Sk—coefficient of skewness; Log. Sk—logarithm of coefficient of skewness.

Sample number	Q_1	M	Q_3	So	Sk.	Log. Sk.
1	.41	.227	.145	1.680	1.16	.0645
2	.72	.410	.28	1.607	1.19	.7750
3	.50	.310	.118	2.050	.615	−.2111
4	.120	.054	.225	2.310	.925	−.0336
5	.1185	.075	.0416	1.67	.880	−.0555
6	.0416	.03131	.0112	1.95	.476	−.3224
7	.0173	.0065	.0019	3.01	.760	−.1192
8	.0130	.0037	.0013	3.16	1.25	.0969
10	.0146	.0039	.0011	3.67	1.04	.0170
11	.0156	.0036	.0010	3.98	1.19	.0755
12	.0156	.0047	.0024	2.73	1.48	.1703
13	.0176	.0112	.0016	3.30	.246	−.6091
15	.0176	.0086	.0025	2.65	.595	−.3255
16	.0173	.0090	.0015	3.45	−.320	−.4949
17	.0196	.0065	.0012	3.58	.393	−.4056
18	.0156	.0052	.0019	2.89	1.100	.0414
20	.0176	.0090	.0020	2.96	.437	−.3595
21	.0138	.0039	.0007	4.44	.635	−.0198
22	.0173	.0060	.0011	3.92	.542	−.2660
23	.0146	.0069	.0032	2.14	.985	−.0066
24	.0233	.0078	.0028	2.89	1.073	.0294
25	.0233	.0073	.0019	3.50	.838	−.0868
26	.0094	.0047	.0013	2.68	.482	−.3179
27	.0090	.0094	.0020	3.08	.433	−.3635
28	.0142	.0073	.0026	2.34	.694	−.1586
30	.0287	.0130	.0052	2.35	.885	−.0521
31	.0190	.0078	.0018	3.21	.575	−.2403
32	.0142	.0039	.0005	5.40	.497	−.3056
33	.0287	.0112	.0019	3.89	.432	−.3645
37	.0730	.0390	.0312	1.52	1.5	.1761
38	.0720	.0416	.0345	1.45	1.43	.1553
39	.0173	.0039	.0009	4.42	1.062	.0261
40	.0156	.0094	.0014	3.33	.25	−.6021
41	.0138	.0060	.0039	1.86	1.49	.1732
42	.0190	.0069	.0036	2.29	1.42	.1523
43	.0242	.0069	.0032	2.74	1.63	.2122
44	.0260	.0115	.0015	4.23	.296	−.5436
45	.3600	.2500	.139	1.61	.800	−.0969
46	16.000	1.500	.37	6.57	2.63	.4200
48	.0156	.0039	.0007	4.65	.738	−.1319
49	.0260	.0071	.0016	4.00	.84	−.0757
50	.0410	.0234	.0104	1.97	1.22	.0864
51	.1045	.054	.0315	1.82	1.14	.0569
52	.2900	.1820	.110	1.62	.9566	−.0195
53	.432	.090	.0364	2.42	.956	−.0195
54	.0350	.0182	.0090	1.97	.950	−.0233
55	.0173	.0116	.0007	5.17	.835	−.0783
56	.0156	.0104	.0007	4.65	1.04	.0170
57	.0190	.0086	.0016	4.23	.412	−.3851
59	.0156	.0073	.0007	4.92	.190	−.7212
60	.0260	.0112	.0052	2.23	1.08	.0334
61	.5000	.280	.2132	1.53	.735	−.1337
62	.0338	.0080	.0025	3.67	1.32	.1206
63	.0173	.0078	.0017	3.16	.497	−.3036
64	.0295	.0138	.0056	2.29	.190	−.7212

TABLE 1—*Continued*

Sample number	Q_1	M	Q_3	So	Sk.	Log. Sk.
65	.0190	.0086	.0021	3.04	.532	−.2741
66	.0540	.0338	.0138	1.98	.658	−.1818
67	.0338	.0190	.0156	1.43	1.45	.1614
70	.0130	.0052	.0016	2.83	.785	−.1051
71	.0118	.0065	.0034	1.86	.890	−.0506
72	.0146	.0047	.0009	4.04	.575	−.2403
73	.0182	.0142	.0025	2.69	1.130	.0531
74	.0180	.0039	.0013	3.72	1.54	.1875
75	.0260	.0190	.0032	2.85	.23	−.6383
76	.0338	.0173	.0039	2.94	.443	−.3536
77	.0260	.0090	.0014	4.30	.45	−.3468
78	.0225	.0065	.0027	2.89	1.53	.1847
79	.0065	.0016	.00012	2.33	3.04	.4289
80	.0180	.0086	.0014	3.67	.362	−.4413
81	.0190	.0060	.0017	3.31	.899	−.0462
82	.0173	.0052	.0007	5.17	.414	−.3830
83	.0130	.0094	.0043	3.02	.632	−.1993
84	.0287	.0078	.0007	6.41	−.329	−.4828
85	.0416	.0410	.0225	1.37	.560	−.2518
86	.0287	.0078	.0019	3.94	.875	−.0580
87	.0225	.0078	.0073	4.16	.482	−.3170
88	.0304	.0173	.0039	2.78	.397	−.4012
89	.3100	.2032	.1145	1.64	.862	−.0645
90	.0173	.0130	.0043	2.82	.54	−.2676
91	.0173	.0073	.0022	2.84	.70	−.1549
92	.0190	.0075	.0015	3.54	.512	−.2907
93	.0416	.0390	.0260	1.265	.71	−.1487

PHYSICAL COMPOSITION OF THE SEDIMENTS IN TERMS OF DIMENSION

Mechanical analyses for composition in terms of dimension were made with U. S. Standard Screen Sieves for particles of sand or greater dimension and with the pipette method of Krumbein (1932) for particles of clay and silt dimension. The unit of sizing is one mm and the ratio is two for particles of sand dimension or larger and one-half for particles of dimensions smaller than sand. The classification is thus according to the Wentworth grade scale. Sediments of shallow water of which the sand content is large are designated sands, the fine soupy materials composing the immediate bottom of deep waters are termed sludge, and the sediments below the sludge are designated muds. The thickness of the sludge is not known, but it probably is of the order of magnitude of one-half to one meter. Nothing is known of the thickness of the sands or the muds. It is known that the old channel of the Wisconsin River is more than 90 meters below the level of the lake, but how much of this consists of melt water deposits of the greater Devils Lake and how much of deposits made since the lake acquired its existing dimensions and outlines have not been determined. The curves showing the sizing of the samples obtained with the Ekman dredge are given in figure 2. The physical constants of medians, quartiles, coefficients of sorting, coefficients of skewness, and log skewness are given in tables 1 and 2.

Of the samples taken on the immediate bottom the median diameters of all samples, except those of numbers 1, 2, 3, 5, 45, 46, 52, 53, 61, and 89, are less than 1/16 mm in diameter, or dominantly these sediments are silts and clays. Samples 1 to 3 and 5 are from

TABLE 2. *Constants of the sizing of samples from cores and sludge*

Q_1 and Q_3—first and third quartiles; M—median; So-coefficient of sorting; Sk—coefficient of skewness; Log Sk—logarithm of skewness. Simple number—sludge, *a—top of core, b—middle of core, c—bottom of core.*

Sample number	Q_1	M	Q_3	So	Sk	Log Sk
9	.0225	.0130	.0022	3.24	.288	−.5406
9a	.0182	.0060	.009	4.53	.449	−.3478
9b	.0156	.0104	.0032	2.21	.462	−.3354
9c	.0190	.0086	.0019	3.20	.487	−.3125
14	.0112	.0047	.008	3.72	.412	−.3851
14a	.0225	.0130	.0032	2.65	.426	−.3706
14b	.0190	.0086	.0017	3.22	.442	−.3546
14c	.0225	.0065	.0043	2.29	2.47	.3727
19	.0173	.0039	.0011	3.91	.745	−.1278
19a	.0156	.0056	.0034	2.14	1.69	.2279
19b	.0190	.0112	.0025	2.76	.379	−.4214
19c	.0243	.0104	.0036	2.58	.801	−.0964
24	.0233	.0078	.0028	2.89	1.07	.0294
24a	.0156	.0060	.0014	3.32	.61	−.2147
24b	.0287	.0120	.0020	3.79	.399	−.3990
24c	.0225	.0112	.0013	4.16	.234	−.6308
29	.0242	.0104	.0020	3.47	.448	−.3478
29a	.0225	.0104	.0056	2.00	1.162	.0652
29b	.0173	.0052	.0009	4.50	.536	−.2708
29c	.0260	.0146	.0094	1.61	1.146	.0577
33	.0104	.0025	.0080	3.72	1.25	.0969
33a	.0137	.0069	.0020	2.54	.547	−.2620
33b	.0190	.0104	.0029	2.51	.512	−.2807
33c	.0208	.0052	.0025	2.88	1.88	.2742
36	.0312	.0181	.0039	2.82	.374	−.4271
36a	.0208	.0146	.0025	2.88	.243	−.6144
36b	.0310	.0156	.0039	2.82	.499	−.3119
36c	.0260	.0112	.0019	3.75	.399	−.3990
94	.0173	.0073	.0043	4.02	1.35	.1303
94a	.0190	.0116	.0035	2.33	.494	−.3063
94b	.0225	.0052	.0017	3.60	1.45	.1614
94c	.0287	.0146	.0056	2.27	.752	−.1238
95	.0104	.0010	.0002	7.21	2.97	.4728
95a	.0190	.0104	.0039	2.21	.685	−.1643
95b	.0190	.0138	.0032	2.43	.320	−.4949
95c	.0287	.0156	.0013	4.70	.154	−.8125
96	.0338	.0104	.0039	2.94	1.21	.0828
96a	.0130	.0052	.00024	7.35	2.49	.3962
96b	.0225	.0112	.0025	3.00	.45	−.3468
96c	.0242	.0138	.0022	3.35	.274	−.5622

the shallow water adjacent to the north shore. These have medians ranging from .075 to .41 mm, or the dimensions are those of fine sands. Numbers 45 and 46 are from the shallow waters of the southeast margin. The median in the sample closest to the shore is 1.5 mm. This is the dimension of coarse sands. The other

sample, taken in somewhat deeper water, has the median of 1/4 mm, or dimension of fine sand. Numbers 52 and 53 are adjacent to the delta of Messenger Creek. The median of 52 is about 1/5 mm and that of 53 about 1/11 mm. These are the dimensions of fine to very fine sands. Numbers 61 and 89 are from shallow water near the east shore and the medians have the dimensions of about 1/5 to 1.4 mm. These are fine sands.

Of the 81 samples there are four which have the first quartiles between .0100 and .0200 mm, and 50 with the third quartile between .0000 and .0050 mm. The coefficients of sorting in 27 of these samples are less than 2.5; these are well sorted. The coefficients of sorting in 46 samples are between 2.5 and 4.5 and these are normally sorted. Only eight samples have coefficients of sorting greater than 4.5 and only these samples may be considered poorly sorted. Some samples have the coefficients of sorting less than two, thus indicating a very high degree of sorting.

The samples of the cores and the sludge at the same place have analyses given in table 2 and the analyses are arranged in blocks to segregate each core. Numbers have the suffixes *a* (top of core), *b* (middle of core), and *c* (bottom of core). Ten cores were analyzed from the positions indicated in figure 1. Medians of all core samples range between .0025 and .0181, and average .0096 mm. The first quartiles are in the range from .0104 to .0338 and average .0212 mm. The third quartiles are in the range from .00024 to .0094 and average .0028 mm. Coefficients of sorting are less than 2.5 in only 9 core samples. These are well sorted. All other samples except 9a and 95, 95c, and 96a have the coefficients of sorting in the range between 2.5 and 4.5 and are thus normally sorted.

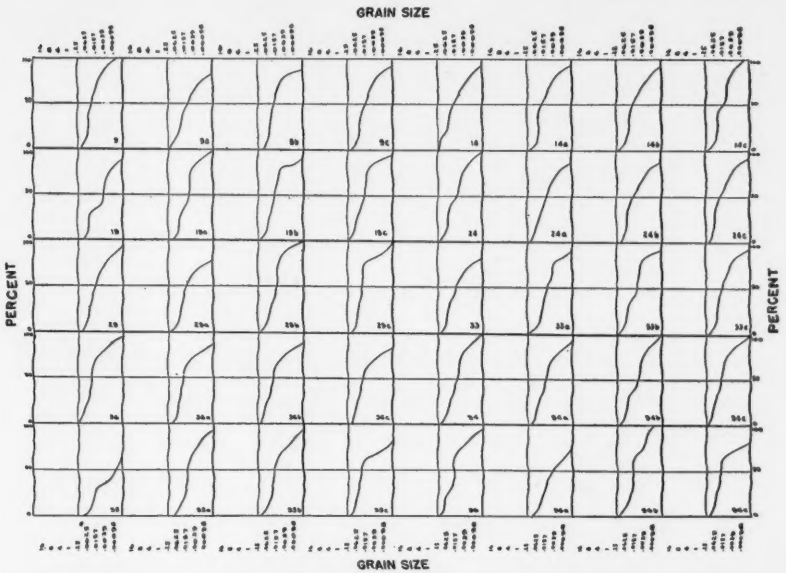

FIG. 3.—*Cumulation curves of the core samples.* Numbers correspond to those of Fig. 1.

Numbers 95 and 96a have coefficients of sorting of 7.21 and 7.35 respectively, thus indicating poor sorting. This arises from the very low values of the third quartile in each. There seems to be no systematic change in sorting with depth. The shapes of the curves show much variation in form as is indicated by the great variations in the skewness of figures. Many curves, however, are very similar.

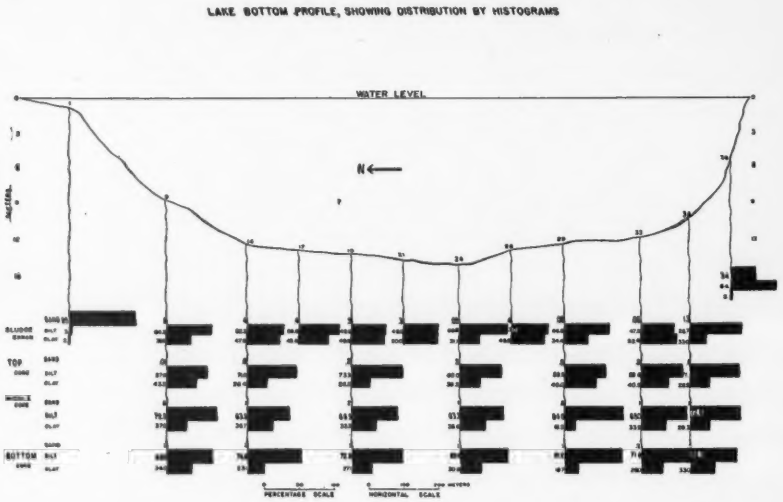

FIG. 4.—Histograms showing distribution of sediments in cores in a profile across Devils Lake.

WATER CONTENT OF CORE SAMPLES

The water contents of the samples of the sludge were not generally determined and no determinations of water contents of sands were made. Determinations were limited to samples from cores. Weighed samples of muds were dried to constant weights at a temperature of about 65°C. for 48 hours. These cores show a small decrease in water content with depth. The tops of the cores represent the first firm mud beneath the sludge. These have a water content ranging from 81.1 to 92.3 per cent, or an average of 87.1 per cent. The samples from the middles of cores range in water content from 76.4 to 91.8 per cent and average 83.1 per cent, four per cent less than the average water content from the tops of cores. Samples from the bottoms of cores have a water content ranging from 75.3 per cent to 86.3 per cent. The average is 82.5 per cent, or nearly the same as the content from the middles of the cores. The total average is over 80 per cent. The water thus approximates a little more than four-fifths of the weights of the muds to a depth of about three meters. Assuming that after compaction one-fifth of the weight would consist of water, only four per cent of the present water would remain and the volume would have decreased to about 25 per cent of that now existing, resulting in a decrease in thickness of about 75 per cent and the thickness of three meters penetrated by the sampler would become 0.75 meter. The

sands that compose the shore deposits would undergo little compaction. These now have stratification that inclines basinward at some angle that is graded to the currents of deposition, and passes into the muds at angles that are graded to the conditions. After compaction the inclinations of stratification at the places of meeting of the sands and muds would undergo increase.

CHEMICAL COMPOSITION OF THE SEDIMENTS

No chemical analyses were made of the sands covering the shallow bottoms adjacent to the shores as these are composed dominantly of quartz. A few shells were seen in a few samples of sands and sludge. After these were removed there was no evidence of presence of carbonates. Analyses were made of sludge and core samples of numbers 9, 14, and 29. The work was done by Mr. W. A. Broughton. The analyses are given in table 3.

TABLE 3. *Analyses of Devils Lake sediments*

Sample number	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	MnO_2	Na_2O–K_2O	Total
9	61.35	3.61	12.08	3.26	0.54	2.37	trace	83.21
9a	57.69	3.36	10.07	2.91	0.75	3.05	trace	77.83
9b	54.57	5.29	11.85	2.36	1.03	2.86	trace	77.96
9c	56.14	4.78	12.35	2.45	1.85	1.72	trace	79.29
14	59.44	5.19	16.56	1.27	2.34	1.95	trace	86.75
14a	54.17	4.16	15.32	0.93	3.14	2.30	trace	80.02
14b	52.32	3.84	12.21	1.08	0.74	2.00	trace	72.19
14c	56.63	3.76	6.28	1.12	1.35	2.10	trace	72.24
29	59.29	5.75	12.60	0.87	2.46	1.74	trace	81.81
29a	52.93	3.85	12.07	0.64	2.30	1.44	trace	84.23
29b	53.98	3.93	13.61	0.48	1.24	2.94	trace	76.18
29c	55.56	2.69	12.53	0.66	2.51	2.51	trace	76.58

The samples contain nitrogen, determined by the micro-Kjeldahl procedure (Kemmerer and Hallet), in the range from 0.018 to 0.88 per cent. It is thought that the differences between the totals given above and 100 per cent is largely organic. Some of the difference may be due to water in clay molecules, or water in opal silica. None is due to decarbonization of carbonates of calcium, magnesium or iron as no carbonate reaction was observed in any of the sediments after shells or bones had been abstracted in the two or three cases where these were seen. It will also be noticed that the total of inorganic matter in the sludge is somewhat greater in samples 9 and 14 than in the samples from the cores but that such is not the case in sample 29. The quantity of silica is essentially the same from top to bottom of cores, but the quantity in the sludge is a little greater than elsewhere. This may be correlated with the recent large contributions of sediments from the atmosphere or by increase in quantity of diatoms. It may also be correlated with concentrations of silica in the shallow water deposits from which the other minerals were washed to deeper bottoms in the early history of the lake and thus later contributions from shallow waters contained a higher content of silica. Were this the case, there should be a progressive increase in the silica content from bottom to top of cores. This is not true. In two samples (14 and 29) the ferric oxide is greater in the sludge than in any core samples, but this is not the case in the sludge from the other sequence (9) where the highest percentage was found

in the sample from the middle of the core. The alumina content seems to show little differences in the sludge as compared with samples from the cores. The calcium oxide is greater in the sludge above each core than in any part of a core, and in each of the three cores analyzed there is a community of percentage from sludge to sample from bottom of core. The magnesium oxide has an irregular and variable distribution and such is also the case for the manganese oxide. Both the calcium and magnesium oxides are thought to be in feldspars and ferro-magnesium minerals that were brought into the region by the ice sheets. Some of the silica is also in these minerals, but much is present as quartz and some as sponge spicules and diatom tests. The content of alumina is slightly variable for all samples except 14c in which the content is about half as large as in other samples.

LOSS OF IGNITION (ORGANIC MATTER?)

As no carbonates seem to be present, no loss on ignition can be referred to this source. The loss is referred largely to organic matter. There are probably some losses due to dehydration of clay minerals and perhaps some to silica in the form of opal. The quantity referable to dehydration of clay minerals and opal is not determinable, but is thought to be responsible for only a small part of the loss. The losses are given in table 4, the numbers representing sludge, top of core, middle of core, and bottom of core respectively. The table also gives the differences between the substance determined by analysis and 100 per cent (table 3). This is in the column designated A (see table 3).

There does not seem to be much system to the quantity of organic matter in the sludge or the core samples. In some cases the quantity in the sludge is smaller than in the core samples, as in numbers 9, 14, 29, and 95. In others, as in number 96 the quantity in the sludge is larger than in any sample from the core of the same sequence. Samples number 19 and 36 are interesting as all the samples in this sequence have nearly the same loss on ignition. The average loss on ignition is 18.8 per cent. The differences between 100 per cent and the common substances determined by chemical analysis for the three sequences do not depart any more from the figures given in losses on ignition than certain samples vary in different tests. Variation to 3 and 4 per cent are common. The average of these figures of differences between the inorganic constituents and 100 per cent is 17.6 per cent, a figure not greatly different from that given above for the average loss on ignition.

THE LIGNEOUS PART OF THE ORGANIC MATTER

The third column of table 4 gives the ligneous part of the organic matter. Determinations were made according to the Steiner and Meloche (1935) method and results are only approximate. Noteworthy is the great variation in quantity, but in no case does the total ligneous matter equal the total loss on ignition. The average is 12 per cent, or about two-thirds of the organic matter as suggested by the losses on ignition. Still more noteworthy is the great variation in the lignin-organic matter ratio. The figure in the latter case would evidently be different if corrections could be made for other losses due to ignition than organic combustion. Under the condition existing in Devils Lake there is little probability of complete decomposition of organic matter taking place over the mud bottoms. The bacterial studies indicate the presence of few decompositional bacteria. The organic matter escaping decomposition would remain to give darkness of color to the sediments.

SHELLS AND TESTS OF ORGANISMS IN THE SEDIMENTS

The sediments do not contain many macroscopic organic remains. A few shells of small gastropods (*Planorbis* and *Physa*) were found in some of the sands of the near-shore shallow water. Two

TABLE 4. *Losses on ignition*

Sample number	Loss on ignition	A	Lignin	Lignin-organic matter ratio
9	12.3%	16.79		
9a	24.0	22.17	17.7	77
9b	23.5	22.04	12.9	55
9c	18.0	20.81	16.1	89
14	14.5	13.25		
14a	21.5	19.98	10.3	71
14b	20.2	17.8	9.7	45
14c	14.7	17.76	11.9	81
19	21.4			
19a	21		10.6	50
19b	21.5		13.0	60
24	19.1			
24a	29.5			
24b	16.6		12.4	75
29	10.9	17.29		
29a	19.7	15.77		
29b	22.0	13.82	10.2	46
29c	21.0	13.42	13.4	64
33	18.9			
33a	20.5		10.9	53
36	14.9			
36a	14.8		10.0	67
36b	14.9		11.4	76
36c	14.0		11.4	81

Sample number	Loss of ignition	Lignin	Lignin-organic matter ratio
94	22.9		
94a	19.3		
94b	18.3	11.7	64
94c	23.7	21.7	91
95	13.2		
95a	22.3	10.0	45
95b	24.5	13.3	54
95c	19.0	8.8	46
96a	21.7	11.3	52
96b	13.5	10.0	74
96c	13.2	7.2	54

fish vertebrae were found in sample 81. These were removed before determinations for carbonates were made. It seems likely that the sparse shell life is confined to shallow water. Tests of diatoms are present but are not particularly common in all samples composed of fine sediments. Spicules of sponges are more common than diatom tests in the ratio of perhaps 10 to 1. It is estimated that together the sponge spicules and diatom tests compose less than 1/100 part of

the materials of the sludge and cores.

OILS IN THE SEDIMENTS

Samples of the sludge and cores were treated with ether and chloroform for determination of oils soluble in these solvents. Gram samples of dried sediments were treated for about 24 hours at room temperatures with the two solvents. The sediments were then filtered and washed and the filtrates evaporated at a temperature below 40°C. Ether in some samples gave a slightly smaller extraction than chloroform and in both methods a variable content was found with depth. The extractions were made on cores 24 and 36 and gave results as shown in table 5.

TABLE 5. *Oil in Devils Lake sediments*

Sample number	Chloroform	Ether
36	.0010%	.0087%
36a	.0025	.0038
36b	.0009	.00056
36c	.0018	.0044
24	.0060	.0015
24a	.0030	.0016
24b	.0086	.0056
24c	.0004	.0008

The quantity is small and ranges from a little more than 1 to nearly 9 pounds per ton. It is not certain that the figures are correct, but the errors, if any, are in the figures being under and not over the actual quantity.

BACTERIA IN THE SEDIMENTS OF DEVILS LAKE

Studies of the bacteria in the sediments of Devils Lake were made by Miss Janice Stadler of the Department of Bacteriology of the College of Agriculture of the University of Wisconsin. A special trip was made to Devils Lake on February 4, 1938, for the purpose of obtaining fresh samples of sludge and cores for the studies. Three cores were obtained and three samples of the sludge, a total of 12 samples. In obtaining the samples the authors were assisted by Mr. H. S. Kunsman, and Miss Stadler took the samples for study as the materials were brought from the bottom of the lake. The stations were in the deepest parts of the lake, that is, where the bottom is about 14 meters deep. The fresh samples were brought to the laboratory in sterile petri dishes and determinations for the aerobic flora were begun immediately and those for the anaerobic flora on the following day. Media and methods used are the same described by Carpenter (1939) and Williams and McCoy (1935). Moisture determinations were made and gave results shown below:

	Core 1	Core 2	Core 3
Sludge	84.56%	86.92%	84.20%
Top of core	81.00	86.28	84.12
Middle of core	80.00	80.72	79.60
Bottom of core	79.64	77.92	79.56
Average	81.41	82.96	81.78

Microscopic examination showed that many varieties of aerobic facultative bacteria are present. There are numerous chromogenic bacteria of which those of yellow and orange colors predominate. The results of the counts are recorded in tables 6 and 7.

Urea fermenting bacteria are very rare and were seen only in the sludge samples of dilution 1–100 and the number of urea fermenters in the core samples is estimated as less than 100 per gram of wet mud. Mesophyllic cellulose

TABLE 6. *Aerobic and facultative counts*
(Dry weight basis)

	Core I	Core II	Core III	Average
Sludge	1,620,000	963,000	975,000	1,182,000

TABLE 7. *Aerobic and facultative counts*
(Wet basis)

Sample	Core number				
	I	II	III	IV	Average
Sludge	250,000	126,000	154,000	—	178,000
Top	−10,000	−10,000	−10,000	104,000	−10,000
Middle	−10,000	−10,000	−10,000	−10,000	−10,000
Bottom	−10,000	−10,000	−10,000	−10,000	−10,000

fermenting bacteria were seen in only two tubes of the entire series. Numbers are given in table 9.

Oxidation products resulting from nitrification were not distinguished. Nitrate tests in cultures grown in ammonium sulphate solution gave negative results and all samples gave negative tests when a drop of the samples was added to three drops of Trommsdorf's reagent and one drop of dilute H_2SO_4. Incubation with absence of light did not intensify the nitrification process enough, if nitrifiers were present at all, to give the blue coloration when Trommsdorf's reagent was added to the nitrates. Bacteria represented by *Nitrosomonas* are very rare in the muds, and are fewer than 10 per gram of wet mud. Other nitrifiers, as *Nitrobacter*, were also found to be absent in dilutions of 1–10. Positive nitrite tests were given with Trommsdorf's reagent. In the presence of nitrates, nitrates could not be determined with diphenylamine. Table 6 gives the aerobic and facultative counts (dry weight basis).

Aerobic nitrogen-fixing organisms are present in the sludge and top samples of cores as determined by microscopic examination. Organisms like *Azobacter* were observed in a 1–10 dilution of the three sludge samples and occasionally in the 1–100 dilution. They were also noted in the 1–10 dilutions of top samples of cores, but they are not representative of these samples. *Clostridium pasteurianum*, representative of the nitrogen-fixing bac-

TABLE 8. *Aerobic counts as determined from the growth in the nitrate solution*

Sample	Core number				
	I	II	III	IV	Average
Sludge	10,000+	10,000+	10,000+	—	10,000+
Top	1,000+	1,000+	1,000+	—	1,000+
Middle	100	100+	100	—	100
Bottom	100	100+	100	—	100

TABLE 9. *Number of urea fermenting organisms*
(Wet basis)

Sample	Core number				
	I	II	III	IV	Average
Sludge	520	1220	1030	—	920
Top	−100	−100	−100	—	−100
Middle	−100	−100	−100	—	−100
Bottom	−100	−100	−100	—	−100

teria, were found by microscopic examination in sludge samples and in a few cases in top to bottom samples of cores. In general, nitrogen-fixing aerobic and anaerobic bacteria are present in the mud deposits of the deeper parts of Devils Lake, but numbers are small.

Denitrifying bacteria are not common and were found only in the sludge. Their presence was determined by formation of nitrogen gas bubbles. No counts were made, but numbers were estimated from surface growths in the medium used for the denitrifying bacteria. Results are given in table 10.

Anaerobes of the *Clostridium butylicum* type were shown to be present by gas production and hydrolysis of starch in corn mash medium. This was obtained in 1–10,000 solutions of the sludge, in 1–1,000 solutions of top samples of the cores, and occasionally in middle and bottom samples of cores in dilutions as low as 1–100.

No work was done on the algae in the muds, but colonies were seen in only

TABLE 10. *Group counts on sample*
(Wet basis)

Group	Sample	I	II	III	IV	Average
Nitrifiers NH_3	Sludge	− 10	− 10	− 10	—	− 10
	Top	− 10	− 10	− 10	—	− 10
	Middle	− 10	− 10	− 10	—	− 10
	Bottom	− 10	− 10	− 10	—	− 10
Nitrifiers NO_2	Sludge	− 10	− 10	− 10	—	− 10
	Top	− 10	− 10	− 10	—	− 10
	Middle	− 10	− 10	− 10	—	− 10
	Bottom	− 10	− 10	− 10	—	− 10
Nitrogen fixers aerobic	Sludge	100	10+	10+	—	100
	Top	10	10	− 10	—	10
	Middle	− 10	− 10	− 10	—	− 10
	Bottom	− 10	− 10	− 10	—	− 10
Nitrogen-fixers anaerobic	Sludge	100	−100	−100	—	− 10
	Top	10	− 10	− 10	—	− 10
	Middle	− 10	− 10	− 10	—	− 10
	Bottom	− 10	− 10	− 10	—	− 10
Denitrifiers	Sludge	−100	−100	−100	—	−100
	Top	−100	−100	−100	—	−100
	Middle	−100	−100	−100	—	−100
	Bottom	−100	−100	−100	—	−100
Mesophilic cellulose fermenters	Sludge	− 10	− 10	− 10	—	− 10
	Top	− 10	− 10	− 10	—	− 10
	Middle	− 10	− 10	− 10	—	− 10
	Bottom	− 10	− 10	− 10	—	− 10
Anaerobes (corn mash)	Sludge	10,000	1,000	10,000	—	10,000
	Top	100	100	100	1000	100
	Middle	−100	−100	−100	−100	−100
	Bottom	−100	−100	−100	−100	−100
Anaerobes (liver)	Sludge	1,000±	10,000	1,000+	—	10,000
	Top	100	1,000	1,000	—	1,000
	Middle	−100	−100	−100	—	−100
	Bottom	−100	−100	−100	—	−100

two of the aerobic plates.

In general, the microscopic flora of Devils Lake is varied but the numbers are small as compared to Lake Mendota, about 40 miles to the southeast, the ratio being about 1 to 85 or 60,000 to 5,200,000 dry weight basis. The kinds are the same. The numbers are somewhat larger than in Crystal Lake, an oligotrophic lake in the northern part of the state (*Carpenter, 1939*).

The greatest number of bacteria are in the sludge. Numbers in the top samples of cores are much less, and middle and bottom samples of the cores contain few bacteria. The average count of sludge samples is 198,000 per gram of wet mud and five to six times that number in a gram of dry mud. This count was obtained by addition of the numbers of the different physiological groups of bacteria. The top samples of the cores on the same basis gave 2,210+ per gram of wet mud or about 13,000 per gram of dry mud. The counts from samples of the middle and bottom parts of cores range to 100 per gram of wet mud or about 500 per gram of dry mud.

Nitrifiers, denitrifiers, and mesophyllic cellulose fermenters are very scarce if present at all, and aerobic and anaerobic nitrogen-fixing and urea-fermenting bacteria are very few in number.

It is suggested that the uncommonness of fermenting bacteria is correlated with poorness of circulation in the deeper waters of Devils Lake, which in turn is referred to absence of a through-flowing stream. Circulation is produced to some extent by currents outward from shores due to turbidity gradients and to the semiannual overturn. However, the former at the present time is probably only occasional and the latter takes place only twice each year. The scarcity of bacteria, in turn, is responsible for preservation of the organic matter and thus it remains with the sediments and they become black as a consequence.

SUMMARY

The sediments of Devils Lake range from clays to sands, are generally well sorted, water content of the fine-grained sediments studied averages 80 per cent or more, the fine-grained sediments are more than 50 per cent silica, there is little or no carbonate, inorganic constituents compose more than 70 per cent, and combined water and organic matter constitute less than 30 and generally less than 25 per cent, the ligneous content of the organic matter is probably more than one half. The muds contain a small content of oily materials. The sediments contain few macroscopic animal remains; microscopic tests and skeletal materials present are diatoms and sponge spicules and these are not abundant. Bacteria are not abundant in the fine-grained sediments. The sediments have basin shape, consisting of sands at the shores and outward to a depth of about 6 meters. Muds and silts are in deeper waters. Stratification is present in the sands. None has been seen in the muds. The fine-grained sediments are very black when wet, and dark gray to gray black when dry. Compaction and lithification would produce dark gray to black shale.

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APPLICATION OF PHOTO-ELECTRIC CELL TO THE MEASUREMENT OF PEBBLE AXES FOR ORIENTATION ANALYSIS

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ABSTRACT

Methods of expressing the size of sedimentary particles are briefly reviewed, and the use of projection areas is chosen as a method of measurement adapted to the study of pebble orientation. A photocell apparatus is described in which pebbles are rotated in a parallel beam of light before the cell. The cell is attached to an ammeter which measures the relative magnitude of the shadow cast by the pebble. Three mutually perpendicular axes are measured, which may be used to express the size of any pebble, however irregular. The axes are defined operationally, to avoid subjective factors in their measurement.

The apparatus is used in connection with a study of pebble orientation, to determine the statistical distribution of the several axes in space, as they occur in the original deposit. For this purpose a triaxial ellipsoid is fit to the axes, and the orientation of the ellipsoid is expressed in terms of its longest axis and the pole of its maximum projection plane. These two reference lines permit the complete orientation of the pebble in space.

By a slight modification of the techniques described, the sphericity values (Wadell) of the pebbles may be obtained by the apparatus.

INTRODUCTION

The problem of expressing the size of irregular solids has received considerable attention from sedimentary petrologists and other workers with particulate materials. The longest, intermediate, and shortest diameters have long been used for pebbles (Wentworth, 1922); for smaller particles the cross-sectional area or various microscopically determined intercepts have been applied. More recently Wadell (1932) reviewed the subject exhaustively, and showed that the simple volume is the most effective measure of size in as much as it is wholly independent of shape.

The following table lists a sufficient number of size concepts which have been used, to indicate the approaches which are possible:

(1) Volume
(2) Weight
(3) Surface area
(4) Projection area
(5) Cross-sectional area
(6) Settling velocity
(7) Intercepts through the particle.

These seven methods include a number of subdivisions. For example, the volume may be used directly to set up volume classes; the cube root of the volume may be taken to obtain a length; or the volume may be expressed as the radius of a sphere having the same volume as the particle (Wadell's *true nominal radius*). Likewise the measurement of intercepts permits many variations; the longest, intermediate, and shortest may be used individually, or they may be expressed as an average, such as the arithmetic, geometric, or harmonic mean (*Roller, 1931*).

For most geological purposes, perhaps, *it is preferable to have a single value to* express the size of the particle. This value *may be used for statistical averages of* size; for studying shape; it may be related to settling velocity; it may be used in studying rates of wear and so on. For such purposes a definition of size not influenced by shape factors is perhaps most appropriate. Wadell's definitions are of outstanding importance in this connection.

For certain studies it is desirable to retain the several "diameters" of the

particle intact, instead of merging them into a single value. This is particularly true of orientation studies (petrofabric analysis) in which the orientation of the pebble in space is to be measured. The obvious choice is the longest intercept through the pebble, which may be expressed in terms of its direction of dip and angle of dip. The complete study of pebble orientation, however, requires more than the alignment of the longest axis. From a given position of the long axis, little or nothing can be predicted about the position of the intermediate or short axis except in restricted cases. The complete orientation can be expressed by a reference line and plane within the pebble. Several choices are possible; the writer uses the longest axis and the maximum projection plane for this purpose, thus combining items (4) and (7) of the preceding list. By means of the definitions to be introduced, the longest axis lies within the maximum projection plane. Normal to this plane is the short axis of the pebble, which is used as the pole of the plane. Hence by measuring the orientation of the long axis directly, and by expressing the orientation of the maximum projection plane in terms of its pole, the pebble is uniquely oriented.

The independence of the long axis and the maximum projection plane, and the need for both to orient the pebble completely, may be seen by considering any triaxial pebble in a sedimentary deposit. For a given orientation of the long axis, the maximum plane may be rotated through any angle about that axis. For example, with a low dip of the long axis, the maximum plane may be essentially horizontal ("flat-lying" pebble), it may be essentially vertical (pebble "on edge") or it may lie somewhere between. Likewise for a given orientation of the plane, the long axis may have various orientations. If the maximum projection plane is inclined, the long axis may be horizontal or it may dip at any angle up to the maximum angle of inclination of the plane. Thus neither the long axis alone nor the maximum plane alone is sufficient completely to describe the position of the pebble in space, except in certain restricted shapes, as discs and cylinders.

The orientation analysis of pebbles on this basis requires first a reliable method of locating the points of emergence of the long and short axes of the pebbles, so that they satisfy the conditions of being normal to each other, and so that the maximum projection area is simply related to the positions of the axes. These conditions may be met purely operationally by measuring the shadows cast by the pebbles in a parallel beam of light. The present paper will describe the apparatus and technique, and will illustrate several uses of the data so obtained. Full details of the collection of oriented samples and the measurement of the orientation in the laboratory are discussed elsewhere by the writer (Krumbein, 1939).

OPERATIONAL DEFINITIONS OF SIZE

Definitions may be grouped into two broad classes. One class is dependent upon a set of postulates or assumptions, and the other is based on a set of operations in the laboratory. The first are theoretical definitions and depend for their acceptance upon the acceptance of the theoretical structure on which they are based. The second type is independent of any theory, and is merely an expression of a set of experimentally noted phenomena. A common example from chemistry illustrates the difference. Isomeric organic compounds may be defined (a) as compounds having the same ultimate chemical composition, but different structural formulas; or (b) as compounds having the same ultimate chemical composition, but exhibiting different chemical properties. The first definition involves an inferred structure of the molecules; the second merely records experimental data.

To obtain operational definitions of pebble size, some objective method of measurement must be devised. The writer's approach involves the use of a photoelectric cell, and a definition of

intermediate and short axes in terms of the shadow cast by the pebble in fixed orientations in a beam of parallel light.

The *operational a-axis* is defined as the longest absolute intercept through the pebble. This is found operationally by rotating the pebble in a sliding block of the type illustrated in Krumbein and in the central frame in such a manner that the operational *a*-axis is vertical. A parallel beam of light from the lamp at the right is intercepted by the pebble, which casts a shadow on the photocell window. An amplifying unit and milliammeter record the relative area of the shadow. As the pebble is rotated about

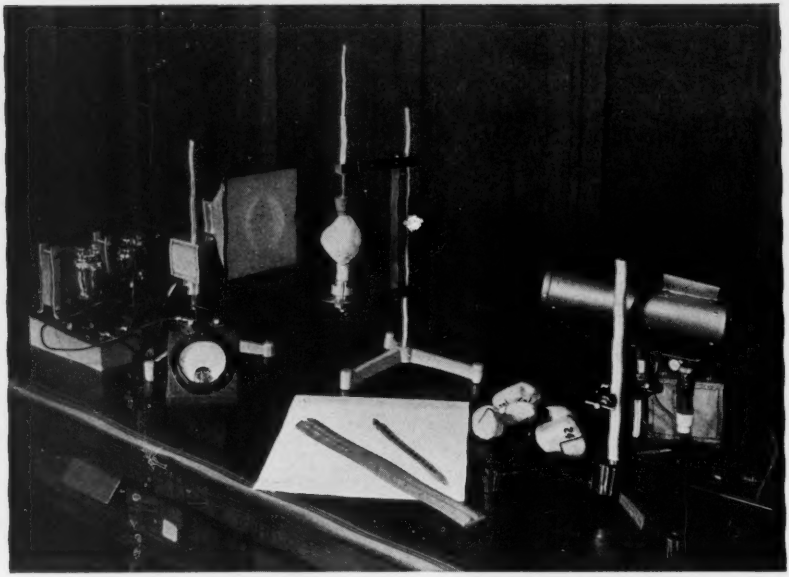

FIG. 1.—Photocell apparatus arranged for measurement of operational axes.

Pettijohn (1938, p. 145), or by means of a caliper. The points of emergence of the axis are marked on the pebble with dots of lacquer. This axis is simply the "longest diameter" as the term is usually used. Among more than 500 beach, stream, and glacial till pebbles measured by the author, very few did not have one axis longer than any other by a measurable amount.

The operational *b*-axis and operational *c*-axis are found by means of a photoelectric cell. The complete apparatus is shown in figure 1. The pebble is mounted the vertical axis, the shadow varies, and hence the ammeter shows a range of readings from maximum to minimum. The exact determination of the *b* and *c* axes depend upon these milliammeter readings.

The frame for supporting the pebbles is shown in detail in figure 2. The support is an ordinary laboratory support, and the frame is made of one-half inch hollow square brass tubing. Through the end of the upper arm a vertical rod is mounted with a spring and an ordinary rubber stopper. On the lower arm is a

brass circle divided into degrees, and supporting a thrust ballbearing to which another rubber stopper is fastened. The pebble is mounted by raising the upper rod and setting the pebble on the lower stopper so that the dot which marks the emergence of the *a*-axis is in the center. The upper stopper is released against the dot at the other end of the pebble. Thus the mount provides for a vertical position of the operational *a*-axis. As constructed, the frame will support pebbles ranging from about 10 to 75 mm long diameter.

The photocell unit is shown in figure 3. It consists of an ordinary photoelectric cell mounted in a pyramidal housing of sheet metal with a ground glass front. The photocell is attached to an amplifying unit* and in turn to a milliammeter, graduated to 0.1 milliammeter. The light

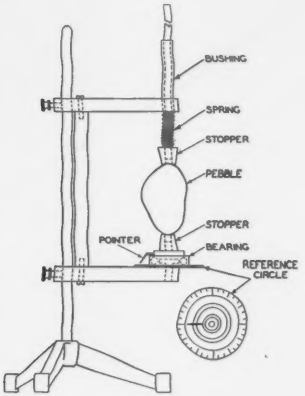

FIG. 2.—Frame for supporting pebbles in photocell apparatus.

source is a parallel beam lamp with a beam large enough to include the long dimensions of the pebbles. For smaller pebbles a template may be used so that the area of the shadow is not too small in comparison to the total lighted area. A "pointolite" which throws a diverging light is also suitable for the small pebbles, inasmuch as it magnifies their shadows, but allowances must be made

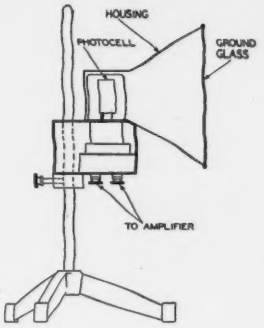

FIG. 3.—Details of photocell housing.

for the degree of magnification. A rheostat in the circuit is useful for controlling the range of readings on the milliammeter.

To measure a pebble, it is mounted in the frame so that it casts its shadow on the cell window. The vertical rod is then rotated slowly until the milliammeter shows its smallest reading. At this point the pebble casts its maximum shadow, and therefore the maximum projection area of the pebble is perpendicular to the beam of light and parallel to the glass on the photocell housing. The *operational b-axis* is defined as the maximum horizontal width of the pebble shadow in a plane parallel to the maximum projection area. It is simply measured by holding a ruler horizontally over the shadow of the pebble on the ground glass and measuring the maximum width of the shadow.

The *operational c-axis* is defined as the maximum horizontal width of the pebble shadow in a vertical plane perpendicular to the maximum projection area. It is found by rotating the pebble 90° from its *b*-axis position on the vertical axis,

* Such amplifying units, ready to attach to a wall socket, are available at no great cost.

and again measuring the maximum width of the shadow on the ground glass. The points of emergence of this axis are marked with lacquer on the pebble. This may be done in a routine manner by rotating the pebble back 90° whereupon the *c*-axis lies parallel to the beam of light. Two soft pencils are lined up with the light beam, one on each side of the pebble. These are checked for horizontality and pressed against the pebble. As long as the dots line up with the light beam the axis is properly located because the maximum plane to which it is normal has an infinite number of poles. The *c*-axis, by definition, is perpendicular to the other two operational axes. These operations yield three intercepts which are mutally perpendicular; one is the longest absolute axis in the pebble and may be used for orientation studies directly; the second lies in a plane parallel to the maximum projection area, and the third is perpendicular to the maximum projection area. It is to be noted, however, that the operational definitions do not require that the three axes intersect at any common point within the pebble.

REMARKS ON THE OPERATIONAL AXES

The choice of axes just mentioned is but one of several choices. In general the result of the operation is three numbers such that $a > b > c$. However, there are some pebble shapes which yield the relation $a > c > b$, so that the *c*-axis is not necessarily the shortest axis. This disadvantage has rarely been encountered in pebbles measured by the writer, but it may be eliminated by a completely rigorous definition, which is however, more tedious to measure. It will be noticed that the present choice of axes depends upon relative readings of the milliammeter. The absolute area of the shadow is not used. The more rigorous choice of axes requires that the milliammeter be first calibrated to read area in square centimeters or square millimeters. This is done by using cards of known area and intercepting the light beam. With care the calibration is reasonably accurate. After calibration, the pebble is rotated to its maximum shadow as before, but the area of the shadow as a whole is read from the milliammeter. The *b*-axis is then defined as the short axis of an ellipse having the same area as the pebble shadow, and the same length as the operational *a*-axis. Likewise the *c*-axis is defined as the short axis of an ellipse having an area equal to the area of the pebble shadow after rotation through 90° from the maximum shadow, and a length equal to the length of the *a*-axis. By this choice the relation $a > b > c$ is always true, and the mutual perpendicularity of the axes is maintained. The tedious computations in this method may be eliminated by preparing a chart in which the long axis is unity, and the ratio of the long to short axes is expressed as a function of area. In the present discussion, however, the axes are measured as first described, and the term "short axis" will be understood always to refer to the operational *c*-axis.

APPLICATIONS OF OPERATIONAL AXES

The operational axes as measured by the photocell represent no radical departure from the well-established long, intermediate, and short "diameters" as usually measured. The only new element introduced is the objective nature and reproducibility of the data, and the control of the angles between the axes. It is difficult to estimate right angles accurately in irregular pebbles, and the photocell accomplishes this with little effort. The process is somewhat time-consuming, but with practice the writer has measured the axes, and marked the *c*-axis on sets of 100 pebbles in about two hours.

In general the operational axes may be used for the same purposes as any other sets of pebble intercepts. That is, the size frequency distributions of the individual axes may be studied, or the distribution of an average pebble size may be used instead. The "average size"

of each pebble may be expressed in several ways. Among these are the arithmetic mean diameter, defined as $d_m = (a+b+c)/3$; the geometric mean diameter, defined as $d_g = \sqrt[3]{abc}$; and, where surface properties are important, the harmonic mean diameter, $m_h = 3\ abc/(ab+bc+ac)$. This latter average is discussed by Roller (1931). In the statistical analysis of the distributions, either the moment or quartile method may be used (Krumbein and Pettijohn, 1938, chapter 9).

The special merit of the operational axes is for orientation studies. Details are given elsewhere (Krumbein, 1939), but in brief the method consists in marking pebbles with reference lines while they are still in the outcrop. In the laboratory the operational *a*- and *c*-axes are located by the photocell method, and the orientation of these axes with respect to the field reference lines is measured with a goniometer. The result is the dip direction and dip of the two axes, referred to the north point of the compass. The long axes are interpreted directly, and the *c*-axes are interpreted as the poles of the maximum projection planes of the pebbles. An example of data from such a study is given later.

The operational axes may also be used to describe the shapes of pebbles. In orientation studies it may be significant to study the degree of preferred orientation shown by pebbles of various sizes and shapes. Shape has been defined in many ways, and among these perhaps the most rigorous is that of Wadell (1932) who expressed shape as a degree of sphericity by comparing the nominal radius with the radius of a sphere circumscribing the pebble. It is also possible to set up indices of shape using the operational axes, although it will be shown later that Wadell's sphericity values may be obtained directly with the photocell apparatus.

EXPRESSION OF PEBBLE SHAPE BY OPERATIONAL AXES

In 1935, Zingg grouped pebbles into four classes on the basis of axial ratios among the long, intermediate, and short axes, using the observed relations between the ratios b/a and c/b. Zingg's grouping is simple and useful, and the classes are readily distinguished:

Class	b/a	c/b	Shape
I	$>2/3$	$<2/3$	tabular (oblate spheroid)
II	$>2/3$	$>2/3$	equidimensional (sphere)
III	$<2/3$	$<2/3$	bladed (triaxial ellipsoid)
IV	$<2/3$	$>2/3$	rod-like (prolate spheroid)

The operational axes defined in this paper may be used in setting up Zingg's classes, inasmuch as the notation and relative values of the axes are the same. Zingg's ratios each involve only two of the pebble axes, and consequently two numbers are required to express the shape of the pebble. Another type of index, which utilizes all three axial values, may, however, be readily defined. If one takes the ratio of the longest axis to some mean of the shorter axes (as the geometric mean) it is obvious that the ratio $a/\sqrt{bc}$ will be large for pebbles in which the *a*-axis is noticeably longer than either *b* or *c*, and hence this ratio may be referred to as the *length-mean ratio*. The denominator $\sqrt{bc}$ is the geometric mean of the two shorter axes. The ratio itself is a pure number with no dimensions. Physically it indicates how many times longer the *a*-axis is than the geometric mean of the *b*- and *c*-axes. A pebble with axes $a = 3.0$ cm., $b = 2.1$ cm., and $c = 1.9$ cm. has the value $3.0/\sqrt{(2.1)(1.9)} = 1.50$, and hence the *a*-axis is 1.5 times as long as the mean of the other two. The ratio $a/\sqrt{bc}$ varies from 1 for a sphere to ∞ for a line. Most pebbles examined by the writer have a value of the ratio between 1 and 2; in order to spread the values more widely over this range the reciprocal of the ratio may be used instead. The reciprocal of the length-mean ratio, the *index of elongation*, E, is thus defined as:

$$E = \sqrt{bc}/a.$$

The value of E varies from 0 to 1. A sphere has unit value; for the example given above, $E = 1/1.5 = 0.67$.

The term "index of elongation" requires some qualifications. It is obvious that if a and b are fixed, but c decreases, E will become smaller. Consequently

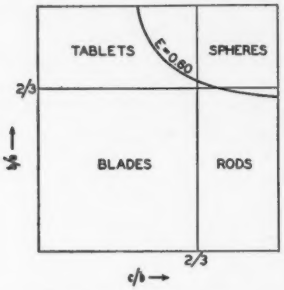

FIG. 4.—Relation between Zingg's pebble classes and the index of elongation.

very thin tabular pebbles (discs) have small values similar to very much elongated ellipsoids. Perhaps the term "anisoaxial index" is preferable, in as much as the index does measure the extent to which the axes are unequal in length, in terms of thickness or breadth of the pebble, or both. There is a definite relation between the index of elongation and Zingg's four classes, but it is doubtful if any single-value function can distinguish among all four shapes. It was found empirically that the value $E=0.60$ segregated blades, rods, and thin tabular pebbles from spheres and thick tablets. This relation is shown graphically in figure 4, and as an arbitrary point of division, $E=0.60$ or less may be taken as an index of markedly inequant pebbles, whereas $E=0.61$ or greater may be used to designate the more equidimensional pebbles.

Wadell has shown (1932) that the "shape" of a particle includes two independent variables, shape and roundness. The index of elongation is essentially a function of shape, and in that respect it is similar to Wadell's sphericity value, except that it is derived from three axial values instead of the volume. Both, however, measure the extent to which particles approach (or depart from) equal dimensions of their axes. The photocell apparatus described in this paper can be adapted to the measurement of Wadell's *degree of sphericity* in a very simple manner. The pebble is mounted as before, and its maximum projection area in square centimeters is read from the calibrated milliammeter. Let this value be A. Then $A=\pi r^2$, where r is the radius of a circle having the same area as the maximum pebble shadow. From the previous measurement of the operational a-axis, the diameter of the circumscribing circle about the pebble is known. Let this value be a. Then the sphericity is simply $2r/a$. This process is based directly on the definition of sphericity in terms of projection area; on this basis the degree of sphericity is the ratio of the radius of a circle having the same area as the pebble projection to the radius of the circle circumscribed about the projection. The number so obtained is designated as ϕ by Wadell.

The index of elongation, as well as other indices of shape, may be studied as any other continuous variable. A frequency distribution of the attribute may be prepared and the average elongation or other statistical measures may be computed; or changes in the index may be studied as a function of distance or time of pebble transport along a stream; or the index may be correlated with the orientation of the pebbles to determine whether any given degree of elongation shows a better preferred orientation than others. To round out the discussion, and as an example of the use of the operational axes, data will be given which test an *a priori* hypothesis that the more elongated (non-equidimensional) pebbles are subject to better orientation by glacial ice than less elongated pebbles.

PREFERRED ORIENTATION OF PEBBLES AS A FUNCTION OF SHAPE

One hundred oriented pebbles were collected from a road cut through a late Wisconsin drumlin near the town of

Random Lake in eastern Wisconsin. The trend of the drumlin indicates that the ice moved essentially from east to west from the Lake Michigan basin. The orientation of the *a*- and *c*-axes was measured on a goniometer as described elsewhere (Krumbein, 1939); for present purposes only the *a*-axes will be used. Figure 5 is a polar co-ordinate chart of the dip direction and dip of the axes. Dip direction (azimuth) is measured along the circumference, and dip is measured along a radius; a point at azimuth 315°, dip 40° indicates that the axis is plunging downward at 40° in a N 45° W direction. The distribution of points indicates an east-west concentration; the mean direction is along the line 85°–265°, and the average spread (measured as the standard deviation, σ) is 41.6°. This means that the average scatter is from 43° to 127° on the east, and from 223° to 307° on the west.

The question is whether the more elongate pebbles cluster about the mean more noticeably than the more spherical pebbles. A simple graphic test may be made. Figure 6 is a scatter diagram made by plotting the index of elongation against the azimuth of dip direction for each pebble. The points are spread rather widely over the diagram, but if they are segregated into elongation classes, the following data emerge:

E	Total pebbles	Number in range $M \pm \sigma$	Number beyond range $M \pm \sigma$	Ratio of in/total
0.2–0.4	5	4	1	0.80
.4– .6	22	15	7	0.68
.6– .8	58	37	21	0.64
.8–1.0	15	9	6	0.60

The number of pebbles in each class is divided into those within the range of one standard deviation unit of the mean, and those without this range. The last column indicates the ratio of those within the range to the total pebbles in each class (column 3 divided by column 2).

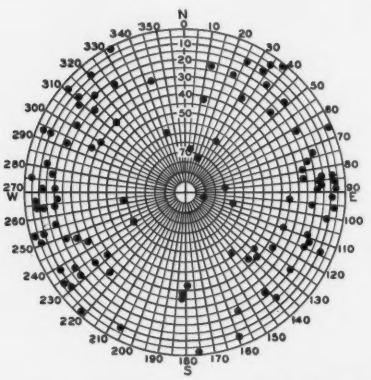

FIG. 5.—Polar co-ordinate chart showing distribution of long a-axes of pebbles from glacial till.

From these data the suggestion is strong that the less spherical pebbles show a better degree of preferred orientation, although the data are hardly sufficient to establish the argument. If the line of division be taken at $E = 0.60$, then the elongate pebbles (E equal to 0.60 or less) have 70.5 per cent within the range,

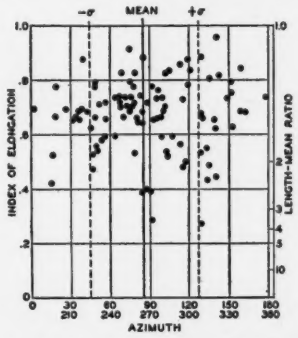

FIG. 6.—Scatter diagram of pebble elongation against azimuth of dip direction.

whereas the less elongate pebbles (*E* equal to 0.61 or greater) have 63.1 per cent within the range.

SUMMARY

Primarily this paper is an attempt to show that older definitions of "size" of irregular particles may be re-expressed on a strict operational basis, to obtain data which are objective and reproducible. The three axes so obtained for each pebble are amenable to the same applications as previously defined concepts. The additional condition of mutual perpendicularity, and an operational method of controlling this condition, permits the use of the axes for orientation studies in such manner that the orientation of particles may be completely described, by means of a line and a plane.

The writer is indebted to Dr. Carl Eckart and Dr. F. J. Pettijohn of the University of Chicago, and Dr. M. K. Hubbert of Columbia University for suggestions and criticisms of the operational definitions used in this paper.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 9, NO. 3, PP. 131–133, FIG. 1, DECEMBER, 1939

DIFFERENTIAL PACKING AS A POSSIBLE DISPLAY OF BEDDING

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ABSTRACT

The possibility that bedding and cross-lamination can be displayed by only an alternation of packing patterns was demonstrated in the laboratory by an artificially deposited clastic "rock." A model of a coarse sandstone built up of uniform wooden balls, thereby eliminating entirely differences in size, shape, and composition of the constituent particles and restricting the differentiating variable to packing, showed bedding. Although this arrangement has not been located in natural rocks, it may be found after appropriate search. Hope for its existence is strengthened by the fact that open and close packing within sands is well known.

Bedding and cross-lamination are recognized in sedimentary rocks wherever a visible difference exists between adjacent, more or less parallel strata or parts of strata for considerable distances. These differences, according to the works on sedimentation are due to variations in (a) composition, (b) size, or (c) shape of the composing particles, and (d) some induration of a bed before deposition of material upon it. Also, changes in color, and differential weathering patterns (because of variation in the nature or amount of cement) are listed by some as factors in production of bedding. These last two, however, are referable, on final analysis, to (*a*), (*b*), and (*c*), usually to (*a*).

When studying the bedding of a sedimentary rock one naturally expects to find the answer to its origin in one of the above categories. However, another possible one discussed below occurred to the writer while studying bedding of the St. Peter sandstone.

The St. Peter is notable, and has been utilized industrially, because of high uniformity within certain parts of the formation, not only in the size of its grains but in their shapes and composition. The cement, chiefly silica, is extremely scanty. Here is one rock, then, in which the differences ascribed to production of bedding appear to be at a minimum; yet, bedding and cross-lamination are very well displayed on its outcrops.

The writer believes that differential cementation, with accompanying or resulting differential weathering, is responsible, in the main, for the display of St. Peter cross-lamination. Nevertheless, throughout the investigation he was continually intrigued with the question whether, if the already high uniformity within the St. Peter has been carried to absolute perfection, any bedding might have shown. To put it more generally suppose all differences in the grains, making up a clastic rock, are eliminated and the rock is built up of particles *absolutely uniform* in size, shape, color, composition, and cement (or packed without cement) will the development of bedding be possible?

An affirmative answer did not seem forthcoming until the idea of variable distribution in space, was considered, i.e., difference in packing of the uniform grains. It is well known that in an aggregate the particles may be open-packed, close-packed, lie in random or haphazard orientation, or may repeat organized packing patterns ranging between close and open packing as shown by Graton and Fraser (1). Perhaps a

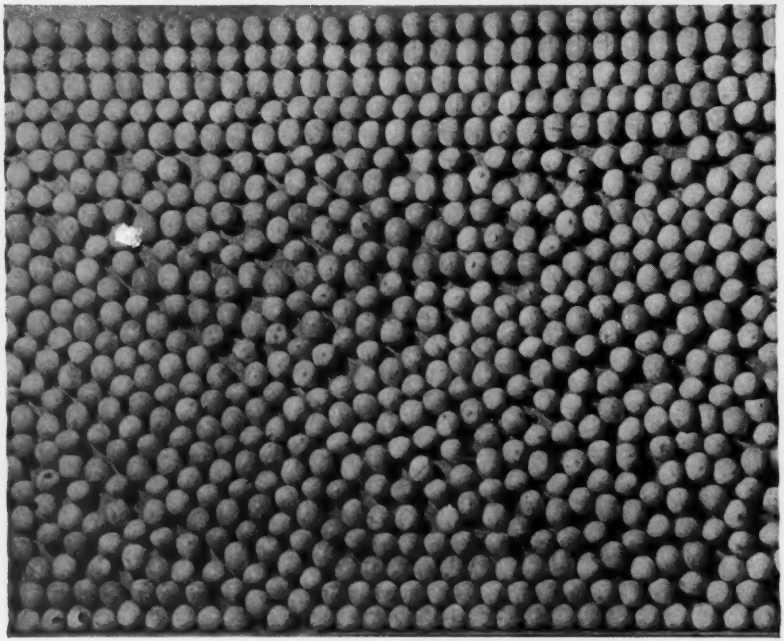

FIG. 1.—Crossbedding shown by variation in packing.

contrast of these packing patterns might give a bedded appearance. The possibility of its occurrence in rocks was strengthened by the thought that sand on the beach or in river deposits may be open-packed (quicksand) or so closely packed as to be firm enough for a road bed, and intercalations of packing might aid in the development of bedding.

To test the idea just presented, it was decided to simulate the deposition of a coarse sandstone, or a conglomerate, from absolutely uniform grains by depositing a number of wooden balls* of one inch diameter in a shallow frame walled in front with a removable pane of glass. The balls were introduced in various ways: by pouring them into the frame, by hand-packing them into position, and by building in with cemented aggregates. Various packing patterns were developed and it was definitely shown that it is theoretically possible for regular-packed beds to be visible in contrast to haphazard aggregates or beds. For ease in visualization most displays were made two-dimensional, i.e., only one layer thick.

In other experiments the frame was tilted back from the vertical to about 40° from the horizontal, the glass front was removed, and the balls located by hand. With this high degree of artificial control several types of hand-picked or handplaced patterns were set up, one of which is shown in figure 1. Here, through the contrast of haphazard packing and two types of cubic packing discernible

* Purchased from Newton and Thompson *Mfg. Co., Brandon, Vermont,* $5.00 per M. These, and other sizes, are useful in the construction of atomic space lattice models.

simulated tangential, cross, and almost horizontal beddings are shown. The regular packing was chiefly hand-placed. Part of the random packing was made by pouring the balls into the frame, other parts are aggregates of balls glued as they lay in haphazard orientation on the floor.

The patterns are fairly clear. They stand out more strikingly when the image is reduced in size. In comparison with a bedded sandstone composed of grains 0.254 mm in diameter the 1 inch balls are 100 times the sand size. The ball model should be viewed in a face 100 times the linear size of the laboratory model and from an appropriately extended distance in order to obtain the same perspective as that from which bedded sandstone is viewed. From that perspective the irregularities would smooth out.

The greatest contrast is between random open packing and a variety of close regular packing. That these packings exist in nature is unquestioned, but whether they are so well set up as these put in place by hand is problematical. The writer has not found an occurrence of cross bedding which can definitely be proved to originate from differential packing, but proof is difficult because of the mechanical or optical difficulties in focusing observation on definite packing planes. Perhaps others studying bedding have or will find evidence in support of this mechanism if consciously looking for it.

Following the pattern in the photograph the most permeable sandstone would most likely be haphazardly packed, whereas that with organized packing would show decreased permeability. This might be a guide to the variations in the field. In retrospect, from a strictly categorical viewpoint, if the interstitial or interparticle medium (air, water, petroleum) is considered an essential part of the rock, the variation in packing with consequent variation in pore filling becomes a special case of variation in composition between parts of the rock and falls under (a) of the first paragraph.

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Leinz, Viktor, *Estudos sobre a glaciação Permo-carbonifera do Sul do Brasil*, Boletim 21, Serviço de Fomento da Producção Mineral, Rio de Janeiro, 1937 (47 pages).

Leinz, Viktor, *Petrographische und geologische Beobachtungen an den Sedimenten der permo-karbonischen Vereisungen Südbrasiliens*, Neues Jarhb. für Miner. etc., 79, 26–62, 1938.

The two papers listed above treat of the same material, and are, except for language, almost exactly identical. The Portuguese version has a few more maps and figures, and some explanations are clearly directed toward a slightly less technical audience. In this paper there is a German summary, which however, would probably not suffice for more than a bare outline of the contents.

The sedimentary study of the glacial deposits is directed along two main lines: (a) the problem of size distribution, with concomitant questions of derivation, and differentiation of glacial and non-glacial sediments, and (b) an investigation of the regularity in alignment of erratics (seixos, Geschiebe).

In the field, measurements were made of the sizes and amounts of the larger constituents. For the finer material, the usual sort of mechanical analysis was carried out. Histograms are given, with a comparison of glacial and doubtfully glacial analyses. Sediments showing two maxima (in place of the usual one) were later found to contain marine fossils, thus proving the usefulness of mechanical analysis. Chemical and heavy mineral analyses of the sediments showed nothing that could be used to unravel their history.

Since most of the usual criteria for determining direction of movement of the ice were lacking, the author has used as a basis of study the regularity of alignment of the long axes of the erratics (seixos, Geschiebe). Each glacial horizon (of the five known) is studied separately, and the results are plotted on a familiar sort of diagram, in which the length of the directive line is proportional to the percentage of blocks lined up in that direction. The figures given show pronounced maxima in a generally N.E.–S.W. direction. From other data the author assumes that movement was toward the southwest.

The source of the glacially deposited material is difficult to find. There is a scarcity of erratics, and the surface from which they originally came has been deeply eroded subsequently. Striations are rare. It is really the presence of a greater number of glacial horizons, and a greater thickness of till to the north and northeast which proves movement toward the southwest. Perhaps the ice came from a region now covered by part of the Atlantic Ocean.

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Study of Materials in Suspension, Mississippi River. Technical Memorandum 122-1, U. S. Waterways Experiment Station, Mississippi River Commission, Vicksburg, Mississippi. 27 pp. of text plus 11 tables (28 pp.) and 83 full-page plates. 8×10 inches, lithoprinted, paper bound. U. S. Waterways Exp. Sta., Vicksburg, Mississippi, February, 1939.

This paper reports the most detailed study yet made of the sedimentary material carried by the Mississippi River. In addition to the usual vertical-type sediment trap, a new horizontal-type sampler was used to trap water and suspended solids from the surface of the stream's bed to a height of several feet above the bottom. Samples were collected on 6 to 11 vertical lines along a surveyed range line across the river. At each of these 6 to 11 "range points," samples were collected at the bottom and

at three inches, six inches, one foot, two feet, and four feet above the bottom, using the horizontal-type trap. Samples were then taken by the vertical-type trap at the surface and at 0.2, 0.4, 0.6, and 0.8 of the measured depth below the "range-point" at the surface and at increments of 0.2 of the depth from the surface to the bottom. Water temperatures were also determined. Ten complete sets of observations were made between January 12, 1937 and May 16, 1938. All observations were made at the Mayersville range opposite Mayersville, Mississippi, 70 miles above Vicksburg.

Total sediment content in parts of sediment (by weight) per million parts of water was determined for all of the samples collected. For all but a few samples, the total parts per million were divided into p.p.m. of "sand" (residue from decantation, greater than 0.0375 mm on the average) and of finer material (silt and clay). Two hundred and twenty-seven of the 615 samples were analyzed for size distribution by a combination of sieving and pipette analysis. A few samples of the bed material were also collected and analyzed for size distribution.

Results of the field observations and laboratory studies are presented in 11 tables and 83 full page plates. The plates include a map showing the position of the ranges, a chart with a continuous record of river stage throughout the period of observation, cross-sections of the stream with velocity and sediment content isarithms, vertical distribution of sediment divided into "silt" and total sediment, and cumulative curves of size distribution.

Not only does this paper present the most accurate information to date on the sedimentary load of one of the world's largest streams, but it also furnishes data on sediment distribution at various points in the stream cross-section with different velocities and river stages which will prove of great interest to students of stream hydraulics and sedimentation. The Mississippi River Commission intends to continue these observations and extend them to tributary streams, so that more complete and even more valuable results may be expected in the future.

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Recent Marine Sediments. A Symposium. Edited by Parker D. Trask. Prepared under Direction of a Subcommittee of the Committee of Sedimentation of the Division of Geology and Geography of the National Research Council, Washington, D. C. Published by the American Association of Petroleum Geologists, 1939, pp. 1–736, text figs. 143.

Part 1 of this important work deals with "Transportation of Sediments" with two contributors: "Transportation of Detritus by Moving Water" by Filip Hjulström and "Effects of Transportation on Sedimentary Particles" by R. Dana Russell.

Part 2 considers the "Relation of Oceanography to Sedimentation" with contributions by R. H. Fleming and Roger Revelle on "Physical Processes in the Ocean" and by H. W. Harvey on "Biological Oceanography."

In part 3 there are considered "Deposits Associated with the Strand Line" and there are four contributions as follows: "Mississippi Delta Sedimentation" by R. J. Russell and R. Dana Russell, "Tidal Lagoon Sediments on the Mississippi Delta" by W. C. Krumbein, "Tidal Flat Deposits (Wattenschlick)" by Walter Häntzschel, and "Beaches" by J. H. C. Martens.

Part 4 treats of "Near Shore Sediments—Hemipalagic Deposits" with articles on "Continental Shelf Sediments" by F. P. Shepard, "Summary of Sedimentary Conditions on the Continental Shelf off the East Coast of the United States" by H. C. Stetson, "Sediments off the California Coast" by Roger Revelle and F. P. Shepard, "Florida and Bahama Marine Calcareous Deposits" by E. M.

Thorp, "Sediments of the Baltic Sea" by Stina Gripenberg, "Sediments of the North Sea" by K. Luders, "Petrological Relations of the Sediments of the Southern North Sea" by C. H. Edelman, "Sediments of the East Indian Archipelago" by P. H. Kuenen, and "Landlocked Waters and the Deposition of Black Muds" by K. M. Strom.

"Pelegic Deposits" are considered in part 5 with contributions on "Pelegic Sediments of the North Atlantic Ocean" by C. W. Correns and "Deep Sea Sediments of the Indian Ocean" by W. Schott.

Part 6 considers "Special Features of Sediments" with contributions on "Rate of Sedimentation of Recent Deep-Sea Sediments" by W. Schott, "Occurrence and Activity of Bacteria in Marine Sediments" by C. E. ZoBell, "Organic Content of Recent Marine Sediments" by Parker D. Trask, "Base Exchange in Relation of Sediments" by W. P. Kelley, "Properties of Clay" by R. E. Grim, "Eolian Deposits in Marine Sediments" by C. E. Radezewski, "Synopsis of Glauconization" by Jun-ichi Takahashi, "Biotite-Glauconite Transformation and Associated Minerals" by E. W. Galliher, and "Faecal Pellets in Relation to Marine Deposits" by H. B. Moore.

The last part, 7, considers "Methods of Study" with contributions on "General Procedure in Studies of Recent Sediments" by W. H. Twenhofel, "Mechanical Analysis" by Stina Gripenberg, "Graphic Presentation and Statistical Analysis of Sediments" by W. C. Krumbein, "Mineral analysis of sediments" by F. J. Pettijohn, "Application of X-Ray Methods to Investigations of Recent Sediments" by Martin Mehmel, and "Bottom Sampling Apparatus" by J. L. Hough.

The book contains author, citation, and subject indexes. An abstract is given for each article of much length. The different articles have been well, but not rigorously edited, and several articles were translated into English from other languages. The articles are well documented with bibliographies.

To attempt detailed consideration of each article of this contribution to knowledge of sediments, sedimentary processes and technique is beyond the limits of a review. The value of each contribution must be left to the judgment of the reader. Contributions by the different writers in some cases present different points of view of the same feature or substance, but this difference of opinion may be considered to add to the merits of the work. Much of the information given in the different articles has previously been published in other places, some of it in foreign journals, but in this work it has been made readily available. Moreover, each article contains much that has not been published before and many of the articles contain new points of view.

This work on the recent marine sediments will be of great value to students of sediments, to classes concerned with studies of sediments, and to geologists concerned with mineral deposits in the sedimentary rocks, particularly the deposits of mineral fuels. The Subcommittee is to be congratulated on completion of the work.

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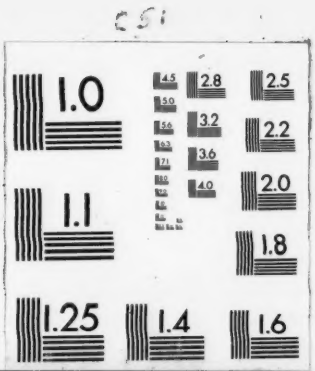
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